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A model for prediction damage due to hurricanes in southern United States

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A MODEL FOR PREDICTING DAMAGE DUE TO HURRICANES IN SOUTHERN UNITED STATES

by

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ABSTRACT

A model for predicting product damage due to hurricanes in the Southern United States is presented. The inputs to the model are the probability density functions for the areal coverage of a hurricane and data regarding the product density in the area. The output of the model is a probability density function for product damage in a given geographical area.

Included in the paper is the derivation of hurricane crossing probabilities and analysis of certain hurricane variables (speed, diameter, and intensity). Finally the model is tested using actual product damage data to determine its validity as a predictor of hurricane damage. The results of this test indicated that the model will predict quite well for the product used in the test.

I. INTRODUCTION

Without any reservations, it can be said that of all disasters caused by weather phenomena, those due to hurricanes have been the most persistent, the most unpredictable, and the most uncontrollable. In recent years the huge loss of life and property (due to increasing population density in the hurricane belt) from hurricanes has become a matter of great national concern. And along with the increasing investment of physical plant in the hurricane belt, industry has also become greatly concerned over the losses incurred during a hurricane. This is particularly true for utility companies who have a large portion of their investment in outside plant equipment which is susceptible to hurricane winds and waters. Utility companies also have a great responsibility to maintain their services during and directly after a hurricane disaster. It is therefore the goal of the utility to protect their equipment from damage and if equipment is destroyed, repair or replace it as quickly as possible to maintain service. While protection of equipment from damage is a responsibility of the designer; the restoration of service is influenced by the availability of men and materials required to affect the repairs. Materials can be obtained from two sources; namely: (1) directly from a manufacturer, or (2) they can be carried as inventory during the hurricane season. The decision as to what source to use is generally an economic one and should be made before the fact. The decision requires knowledge of what materials may be required and how much may be required. In general, a knowledge of the expected damage in a given time period is required to make this decision. It is therefore the objective of this paper to present a method for predicting the level of expected damage due to hurricanes during a hurricane season.

In order to predict the level of damage, a model will be developed whose parameters are determined based on historical data. The model so developed is a function of the expected areal coverage of a hurricane, the product density for the product under consideration, and a product "hardness" factor. The model, as presented, is very general in an attempt to smooth the extreme variability inherent to hurricanes. The output of the model is a probability density function for the level of hurricane damage for given geographical areas for one hurricane season.

The model will be tested using actual data obtained for the number of telephone stations affected by hurricanes. The results obtained are valid only for the product with its unique product density. However, the model can be applied to any product and the techniques shown in this paper will be generally applicable to all products.

The reader will note as he reads this paper the over-usage of the words sometimes, usually, average, about, probably, etc. These words are necessary since nothing about hurricanes is known with any certainty except that we will continue to have hurricanes in the future and they will cause an increasing amount of damage. Due to this uncertainty and variability, all final numerical results will not be carried beyond one decimal place except, in a few isolated cases where accuracy dictates. Intermediate results have been carried to four decimal places to reduce the accumulating effects of rounding. The diagram shown in Figure 1 indicates the major divisions of this paper and their relationship to one another. It will help the reader to keep this diagram in mind when reading this paper.

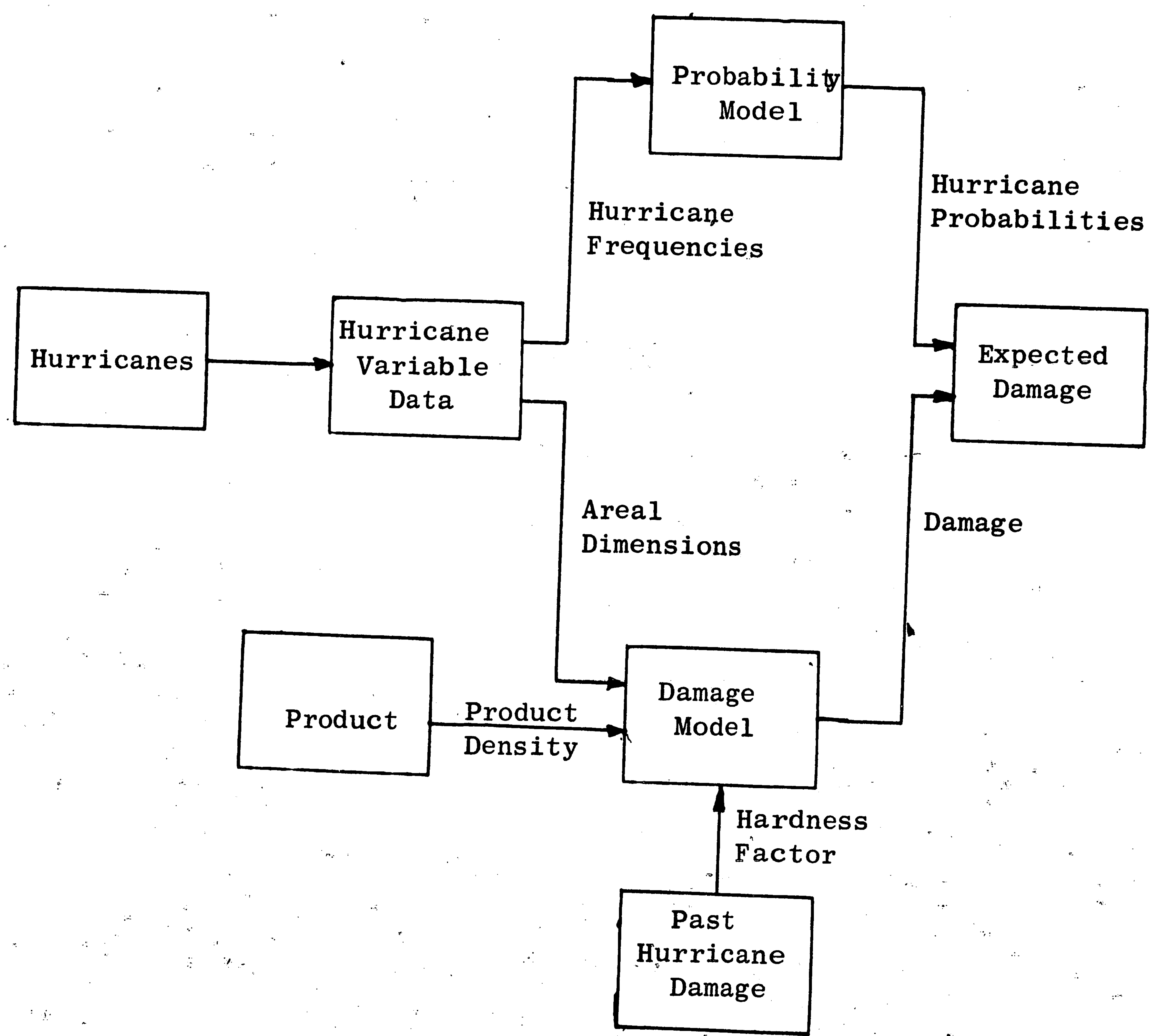

Figure 1.

II. OBJECTIVES

The major objective of this paper is to present a model for predicting, within a confidence interval, physical hurricane damage for a hurricane season. It is hoped that the validity of the model, as a damage predictor, can be ascertained as a final conclusion. There are two other objectives which support the major objective but are important in their own right. They are

1. Gather available data on hurricane variables and present in a meaningful form under one cover, and
2. analyze the data on hurricane variables on a statistical basis.

These two sub-objectives serve three purposes; namely,

1. The data and data analysis are required as inputs to the damage model.
2. Anyone doing further work in this area will have the data tabulated all in one place or at least know where to go to obtain additional information. This is felt to be extremely important since this paper presents, to the authors knowledge, the first major work in this area for the purpose of making a decision concerning inventory for repairing hurricane damage.
3. In the hurricane literature, there have been conclusions drawn concerning the functional relationship of variables based on "best fit" curves through the data. These relation-

ships will be looked at from a statistical viewpoint to determine the validity of these conclusions.

With the above objectives in mind, we are ready to proceed with the analysis and model formulation.

III. HURRICANES (General)

Hurricanes,* the most widely destructive of all storms, are great vortices of air swirling in a counterclockwise direction around a nearly calm center. Those storms that affect the United States usually form in the southern portion of the North Atlantic, the Caribbean Sea, or the Gulf of Mexico and are accompanied by violent destructive winds, heavy rains, and mountainous seas.

Tropical revolving storms when first formed are usually embedded in the trade winds that blow from an easterly direction, between ten and twenty degrees north of the Equator. They, therefore, move generally toward the west. After gradually increasing in size and intensity, these storms usually curve toward the north and then northeast. They may either strike the eastern coast of the United States or travel out over the North Atlantic with the prevailing westerlies found in the more northern latitudes. In other cases the storms may continue their westward movement across the Caribbean Sea or the Gulf of Mexico to reach the coasts of Central America, Mexico, or the Gulf states. The fastest and, therefore, the most destructive winds of a hurricane blow counterclockwise in a band twenty or fifty or more miles wide around the storm's center, the "eye," where the winds are light or even calm for a brief time. In this band or ring of violent

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* For reference material see I. R. Tannehill, Hurricanes, 8th rev. ed. (Princeton, N. J.: Princeton University Press, 1952); Hurricane Hunters (New York: Dodd, Mead & Co., 1955); Malcom Rigby (Ed.), Meteorological Abstracts and Bibliography (Boston, Mass.: American Meteorological Society); reports, technical papers, and other informational material issued by the U. S. Weather Bureau, Washington, D. C. Also see bibliography at end of this paper.

winds, velocities at the surface of the earth may reach 130 miles per hour, with brief gusts to 150 miles per hour. Beyond the zone of highest winds, the winds decrease as the distance from the hurricane's center increases. Frequently there are large differences in wind speed in the four quarters of a hurricane, with the strongest winds in the right forward quadrant of the advancing storm.

As a hurricane moves northward out of tropical waters, the forward speed of the entire storm usually increases, occasionally to a marked degree. For example, the famous 1938 New England hurricane and the equally famous Hurricane Carol of 1954 rapidly increased their forward speeds after passing Cape Hatteras, until they were moving at more than fifty miles per hour when they hit the New England coast. With some hurricanes, on the other hand, there is for a time practically no forward movement of the storm's center, so that the hurricane winds blow steadily over the same area for hours or even for a day or two. In unusual cases the hurricane may go through one or more loops or hairpin curves or move from north to south or double back to strike the same land area twice.

The width of destruction caused by the winds of a hurricane as it moves over or near land varies considerably. In a small hurricane the region of major destruction may be less than twenty-five miles wide, but in great hurricanes it may be two hundred miles wide and up to a thousand miles long. High water brought on shore by a hurricane has caused great loss of life and property. A century of records shows that more than three fourths of all deaths in hurricanes can be attributed to drowning in coastal high waters brought in as storm surges. Water eight to eighteen feet above normal tides has been recorded during some of the larger hurricanes along the Gulf and Atlantic coasts. These wind-driven storm surges can also cause sudden rises in water levels outside the storm's center, usually to the right of the path of the hurricane as it approaches the coast. Local topography, as well as the path, speed, and intensity of the storm, can increase or decrease the effects of storm surges and account for wide variations in water damage over short coastal stretches.

Hurricane rains are responsible for many of the major inland floods that have occurred in the Gulf and Atlantic Coast states. The most intense twenty-four-hour rainfall from a hurricane in the United States occurred in September 1921, when 23.11 inches fell on Taylor, Texas. Up to twenty inches of rain fell on parts of Connecticut and Massachusetts during the final phases of Hurricane Diane in August 1955. The average life span of a hurricane is about nine days. August hurricanes have the longest average life span, twelve days; and July and November hurricanes normally last only about eight days from origin to disappearance.

The hurricane season ranges from June to November with isolated occurrences in May, December, and January with the principal months being August, September, and October.

In recent years the widespread hurricane reporting system has probably observed all well developed tropical storms; and before the reporting network was so well organized, a few tropical storms may have escaped observations. Therefore, statistics comparing hurricane frequency in recent years with earlier years may be misleading. For the past eighty years the greatest number of tropical storms to attain hurricane intensity in any one year was eleven (1950). In 1893 and 1950, four hurricanes were in progress at the same time, including occurrences in the Gulf, the Caribbean, and the western Atlantic. The annual average for the time period is four with annual average of 1.92 hurricanes reaching the United States coast.

IV. DEFINITIONS

This section is devoted to two definitions, the first being a definition of a hurricane and the second defines the geographical area under study.

4.1 Hurricane Definition

For the purpose of this study a hurricane will be defined as follows:

> A hurricane is a tropical storm which has a wind speed greater than or equal to 75 miles/hour and has a barometric pressure less than or equal to 29.40 inches of mercury. Both the wind speed and barometric pressure to be measured at the 10 foot level.

The above definition is consistent with the Beaufort Scale definition and corresponds to a Beaufort number of 12 or greater.

4.2 Geographical Area Included In This Study

The area of hurricane activity in the United States extends from the southern tip of Texas around the Gulf to Key West, Florida and along the entire Atlantic coastline to Canada. The area of greatest activity occurs along the Gulf coast and along Atlantic coast south of Cape Hatteras, North Carolina. In order to reduce the area to a more manageable size and still include the areas of greatest activity it was decided to limit this study to the area south of the 35th parallel along the Atlantic coast and the entire Gulf coast. This area was then partitioned into 5^{o} squares (5^{o} longitude by 5^{o} latitude) as shown in Fig. 2. Each 5^{o} square (not quiet a square) includes approximately 100,000 square miles and approximately 300 miles of coastline. Partitioning of the area becomes necessary since there exists significant differences in the values of some of the hurricane variables from one square to the next.

Each 5^o square will be referred to hereafter as a zone with the numbering system shown in Figure 2, where zone i includes the same area as square i. Later in the study it will become necessary to combine zones 4 and 5 and the new enlarged zone will be referred to as zone 4. Also, at the same time, zone 6 will be referred to as zone 5 to allow summation over all zones to be placed under one summation sign. The entire area (zones 1 through zone 6) will be referred to as the Southern United States hereafter.

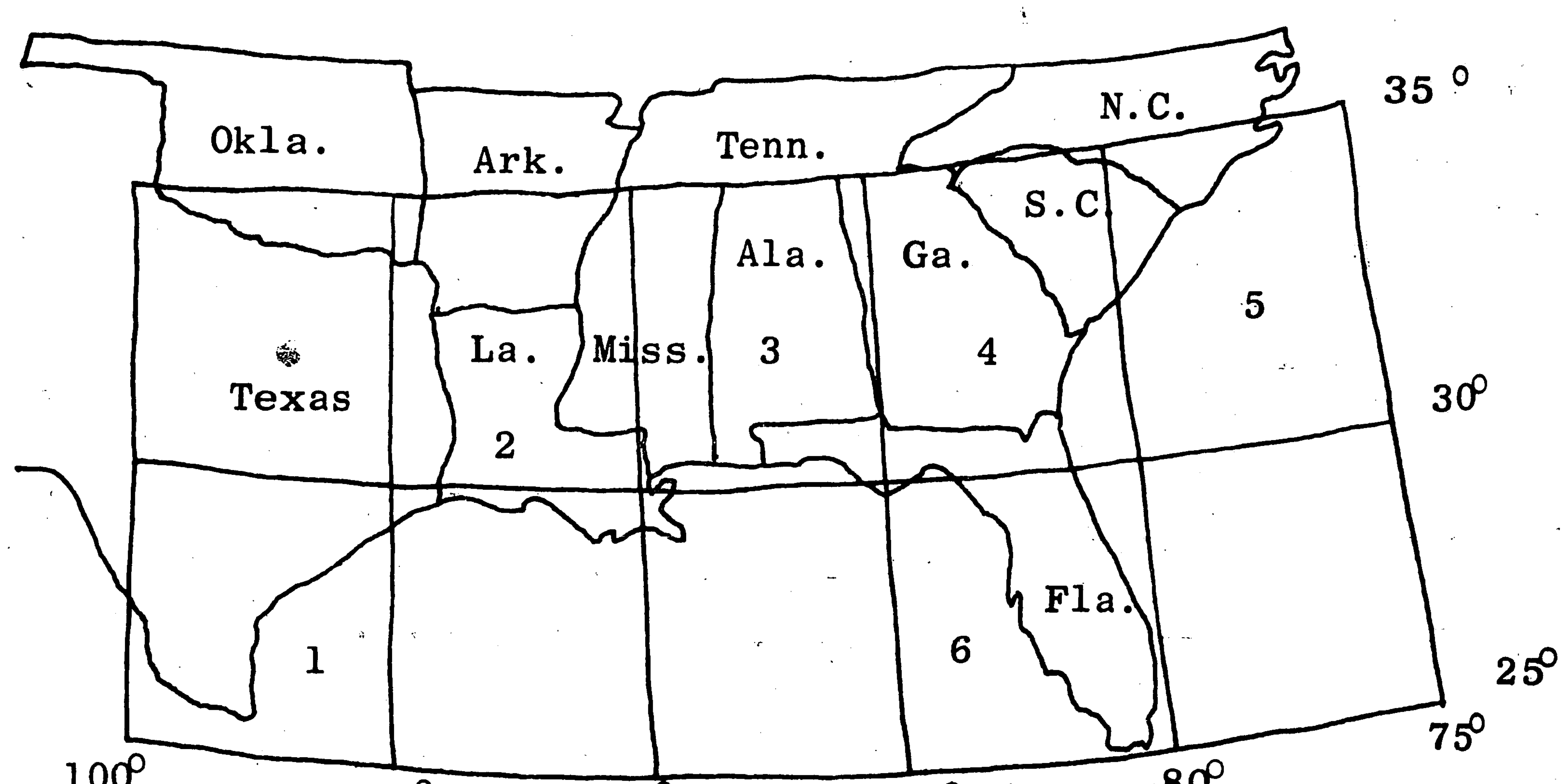

Figure 2. Geographical Area In This Study

V. NOTATION

The following notation will be used throughout this paper. Due to the large number of variables present, the reader is urged to keep this section at his fingertips as he reads through the remainder of the paper.

Symbol	Description
X_i	Level of hurricane damage, given one hurricane passes through zone i, in units of product. Mean - μ_{X_i} Variance - $\sigma_{X_i}^2$
$\bar{X}_i$	Level of hurricane damage in zone i for one hurricane season in units of product. Mean - $\mu_{\bar{X}_i}$ Variance - $\sigma_{\bar{X}_i}^2$
Z	Estimated level of damage for the entire Southern United States for one season (in units of product). Mean - μ_Z Variance - σ_Z^2
Y	Number of hurricanes reaching the United States coast in one season. Mean - $\mu_Y = \lambda$ Variance σ_Y^2
h(t)	Number of hurricane crossings in month t in the time period (1887 - 1960).
p[h(t)]	Probability of a hurricane corssing in month t in any hurricane season given that a hurricane will cross the United States.
h_i	Number of hurricane corssings in zone i in the time period (1887 - 1960).
$p(h_i)$	Probability of a hurricane crossing in zone i in any hurricane season given that a hurricane will cross the United States.

Symbol	Description
$p[h_i(t)]$	Probability of a hurricane crossing zone i in month t in any hurricane season given that a hurricane will cross the United States.
$p_2(h_i)$	Probability of a hurricane crossing zone i and that it has crossed zone 6. Two zone probabilities.
D_i	Diameter of a hurricane in zone i in miles. Mean - μ_{D_i} Variance - $\sigma_{D_i}^2$
T_i	Duration of hurricane winds over a land mass after a hurricane encounters the coast (in hours). Mean - μ_{T_i} Variance - $\sigma_{T_i}^2$
C_i	Central Pressure Index of a hurricane in zone i (inches of mercury). Mean - μ_{C_i} Variance - $\sigma_{C_i}^2$
S_i	Forward speed (miles/hr) of a hurricane in zone i. Mean - μ_{S_i} Variance - $\sigma_{S_i}^2$
R_i	Product density in zone i (units/sq. mile). Mean - μ_{R_i} Variance - $\sigma_{R_i}^2$
α	Hardness factor.
A_i	Areal coverage of a hurricane in zone i. Mean - μ_{A_i} Variance - $\sigma_{A_i}^2$
r	Wind adjustment ratio
C_i^1	Transformed Central Pressure Index for zone i. Mean - $\mu_{C_i^1}$ Variance - $\sigma_{C_i}^2$
P_i	Population density in zone i in 1960.

Symbol	Description
γ_i	Bell system telephones per person in zone i.
X^2	Chi-Squared variable.
small letters	Constants

VI. HURRICANE PROBABILITIES

Hurricane probabilities are required to find the expected damage. In the damage model section we will determine the expected damage given a hurricane, and this quantity multiplied by the probability of a hurricane gives the expected damage.

6.1 Hurricanes Reaching U. S. Coast

Frequency data[1,2] was gathered for the number of hurricanes reaching the United States coast for years 1867 to 1960 inclusive and is shown in the Appendix in Table XIII.

It was hypothesized that the number of hurricanes reaching the United States coast in a year was a Poisson variable Y with mean μ_Y and variance σ_Y^2. Before a test was made to determine the validity of this hypothesis, the data was tested to determine if the observations were drawn at random from a single population. The run test[3], distribution-free technique, was employed with the following results:

H_o: Randomness of sample data

Median at = 2.0

Number of minus signs = 27

Number of plus signs = 22

Number of runs = 15

At a 5% significance level, the number of runs was found to be less than the critical value[4], and the hypothesis H_o was rejected.

Therefore, to determine the type of dependency in the sample data a ten-year moving average was taken for the mean and variance and plotted as shown in the appendix. It was found that the mean had moved upward and the variance had moved downward with both the mean and variance exhibiting a 20-25 year cycle. It was also noted that there exists a downward step in the variance around 1940 which prompted a decision to use only the data from 1940 to 1960, and it was hypothesized that this data was random and tested, as before, only to find that this hypothesis also had to be rejected. It was finally concluded that the data was not drawn at random from the same population. However, due to the inaccuracies in reporting hurricanes prior to 1950, the assumption of randomness in the data shall be maintained until new information either supports or rejects this assumption.

To test the hypothesis that Y is a Poisson variable, the following procedure was followed:

1. Table I was formed from Table XIII in the Appendix.

TABLE I Frequency Table for Y

Y	Observed Frequency of Y
0	12
1	15
2	24
3	16
4	3
5	1 } 4
6	3 }
Total	74

2. The mean μ_Y was estimated from Table I and found to be $\mu_Y = 1.97$.

3. The data in Table I was tested against a Poisson distribution (with $\lambda = 1.97$, using the Chi Squared Goodness of Fit test at the .95 level).

The following results were obtained:

$$X^2 \text{ (calculated at } \lambda = 1.97) = 5.03$$

$$X^2 \text{ (.95 level, 4 dof)} = 9.49$$

Since X^2 (calculated) $< X^2$ (.95 level, 4 dof), the hypothesis that Y fits a Poisson variable <u>cannot</u> be rejected. Therefore:

$$f(Y) = \frac{e^{-1.97}\,(1.97)^Y}{Y!} \qquad Y = 0,1,2,3, \ldots$$

$$\mu_Y = \sigma_Y^2 = 1.97 \qquad (6\text{-}1)$$

6.2 Probabilities By Zone and Month

To calculate the probability of a hurricane by zone and month, the frequency data[1,2] was obtained for the years 1887-1960. This data is in terms of the total number of observed hurricane crossings within a zone by each month of the hurricane season. Since a hurricane can cross several zones, the total number of crossings is greater than the total number of hurricanes reaching the coast. This data is shown in Table II with the notation set forth earlier in this paper.

TABLE II. Hurricane Crossing by Month and Zone (1887-1960)

		Month	June	July	August	Sept.	Oct.	Nov.	Total	
	Zone		$h(1)$	$h(2)$	$h(3)$	$h(4)$	$h(5)$	$h(6)$	n_i	$p(h_i)$
	1	h_1	9	8	11	10	5	0	43	.092
	2	h_2	3	6	8	17	4	1	38	.142
	3	h_3	5	8	11	24	10	1	59	.188
h_i	4	h_4	5	7	11	30	23	2	78	.227
	5	h_5	6	9	14	30	31	4	94	.104
	6	h_6	9	7	15	31	35	5	102	.247
	$n(t)$		37	45	70	142	108	12	414	
	$p[h(t)]$		.089	.109	.169	.343	.261	.029		1.000

Referring to Table II, it is noted that

$$n_i = \sum_t h_i(t)$$

$$n_t = \sum_i h_i(t)$$

$$N = \sum_i n_i = \sum_t n(t) = 414$$

and

$$p[h(t)] = \frac{n(t)}{N}$$

$$p(h_i) = \frac{n_i}{N}$$

The desired probability is denoted $p[h_i(t)]$, and if h_i and $h(t)$ are independent then

$$p[h_i(t)] = p(h_i)\, p[h(t)] \tag{6-2}$$

where $p(h_i)$ and $p[h(t)]$ are the marginal probabilities of the joint probability $p[h_i\ (t)]$. To test for independence between h_i and $h(t)$, Table II was treated as a 6 x 6 contingency table, and a statistical test for independence was performed in the following manner:

1. A table of expected frequencies was prepared in which each expected cell frequency as calculated in the following manner:

   For the i,tth cell, $h_i(t) = \dfrac{n_i n(t)}{N}$

   e.g., to find the expected frequency for August in Zone 6, we have (from Table II)

$$h_6(3) = \frac{n_6 n(3)}{N} = \frac{(102)(70)}{414} = 17.3.$$

2. A value for X^2 (Chi-square) was then calculated, where

$$X^2 = \sum_i \sum_j (O_{ij} - E_{ij})^2 / E_{ij} \tag{6-3}$$

   where O_{ij} - i,jth cell observed frequency

   E_{ij} - i,jth cell expected frequency.

3. The value obtained for X^2 in (2) has (5)(5) = 25 degrees of freedom, and if $X^2 > X^2_{(.95)(25)}$ the hypothesis of independence will be rejected.

   Results: X^2 (from Table II) = 39.95

   $X^2_{(.95)(25)} = 37.7$

Since $X^2 > X^2(.95)(25)$

Reject independence hypothesis

It can be concluded from this test that some dependence exists between the variables h(t) and h_i. Since h(t) and h_i are dependent, it is apparent then that $p[h_i(t)]$ must be derived from the conditional probability

$$p[h_i \mid h(t)] = \frac{p[h_i(t)]}{p[h(t)]}$$

or

$$p[h_i(t)] = p[h_i \mid h(t)] \cdot p[h(t)] . \qquad (6\text{-}4)$$

Table II can be used to derive estimates for $p[h_i \mid h(t)]$ and $p[h(t)]$. Using equation (6-4), values for $p[h_i(t)]$ are derived and shown in Table III.

TABLE III. Hurricane Probabilities by Zone and Month, $p[h_i(t)]$

Month		June	July	August	Sept.	Oct.	Nov.	
Zone		h(1)	h(2)	h(3)	h(4)	h(5)	h(6)	$p(h_i)$
1	h_1	.022	.019	.027	.024	.012	.0	.104
2	h_2	.007	.014	.019	.041	.010	.002	.093
3	h_3	.012	.019	.027	.058	.024	.002	.142
4	h_4	.012	.017	.027	.072	.056	.005	.189
5	h_5	.014	.022	.034	.072	.075	.010	.227
6	h_6	.022	.017	.036	.075	.083	.012	.245
$p[h(t)]$		.089	.108	.170	.342	.260	.031	1.000

Table III is to read as follows: The probability of a hurricane crossing zone 6 (Florida) in month 4 (September) or $p[h_6(4)]$, given one crossing, is located at the intersection of the September column and zone 6 row. For this case,

$$p[h_6(4)] = .075$$

or there is a 7.5% chance that the crossing will be in Florida and in September.

It is interesting to compare the marginal probability $p[(h(t)]$ in Table III to the marginal probability of a hurricane based on the total number of hurricanes (not land mass crossings); this comparison is shown in Table IV.

TABLE IV. $p[h(t)]$, Comparison of Crossings and Total Number of Hurricanes, Same Time Base

	June	July	August	Sept.	Oct.	Nov.
$p[h(t)]$	h(1)	h(2)	h(3)	h(4)	h(5)	h(6)
Based on Crossings	.089	.108	.170	.342	.260	.031
Based on Hurricanes	.052	.075	.294	.357	.186	.036

It is felt that the probabilities based on crossings is the more realistic case when one considers that the hurricanes can cross one or more zones. The probabilities set forth in Table III will be used hereafter in this paper.

6.3 Two-Zone Crossing Probabilities

From the literature it was noted that a hurricane crossing zone 6 (Florida) will usually cross another zone. While there have been cases where a hurricane crossing Florida will curve back out into the Atlantic and then stay at sea or else pass into one of the northern states, it will be assumed that a hurricane corssing zone 6 will cross one and only one of the other five zones considered in this study. The probability of this occurrence for zone i is denoted $p_2(h_i)$ with the assumption that $p_2[h_i(1)] = p_2[h_i(2)] = \ldots = p_2[h_i(6)]$ where i = 1, 2, 3, 4, 5. The probability $p_2(h_i)$ is found by the ratio of the probability of zone i crossing $(p(h_i))$ to the total outcome space $(1-p(h_6))$. This ratio is then normalized by multiplying by $p(h_6)$ for all i since $\sum_{i=1}^{5} p_2(h_i) = p(h_6) = .245$. Performing the above operations yields:

$$p_2(h_i) = \frac{p(h_i)\cdot p(h_6)}{1 - p(h_6)} \tag{6-5}$$

$$p_2(h_i) = \frac{.245}{.755}\, p(h_i). \tag{6-6}$$

From equation (6-6) the probabilities for $p_2(h_i)$ were calculated as shown in Table V.

TABLE V. Two Zone Crossing Probabilities (Probability of a hurricane crossing zone i and it has crossed zone 6)

Zone i	$p_2(h_i)$
1	.034
2	.030
3	.046
4	.061
5	.074
$\sum_{i=1}^{5} p_2(h_i)$	.245

6.4 Probabilities by SMSA*

Shown in the Appendix is a map of the SMSA's in southern United States with a 5^o grid superimposed to indicate the relative locations of the SMSA's to the zones. The desired probability, denoted $P_{(SM)}$, is the probability that a hurricane will pass through a SMSA given that it enters a zone in a manner consistent with the assumptions set forth in this section.

To derive this probability, let us take a look at a typical zone and its SMSA's as shown in Figure 3.

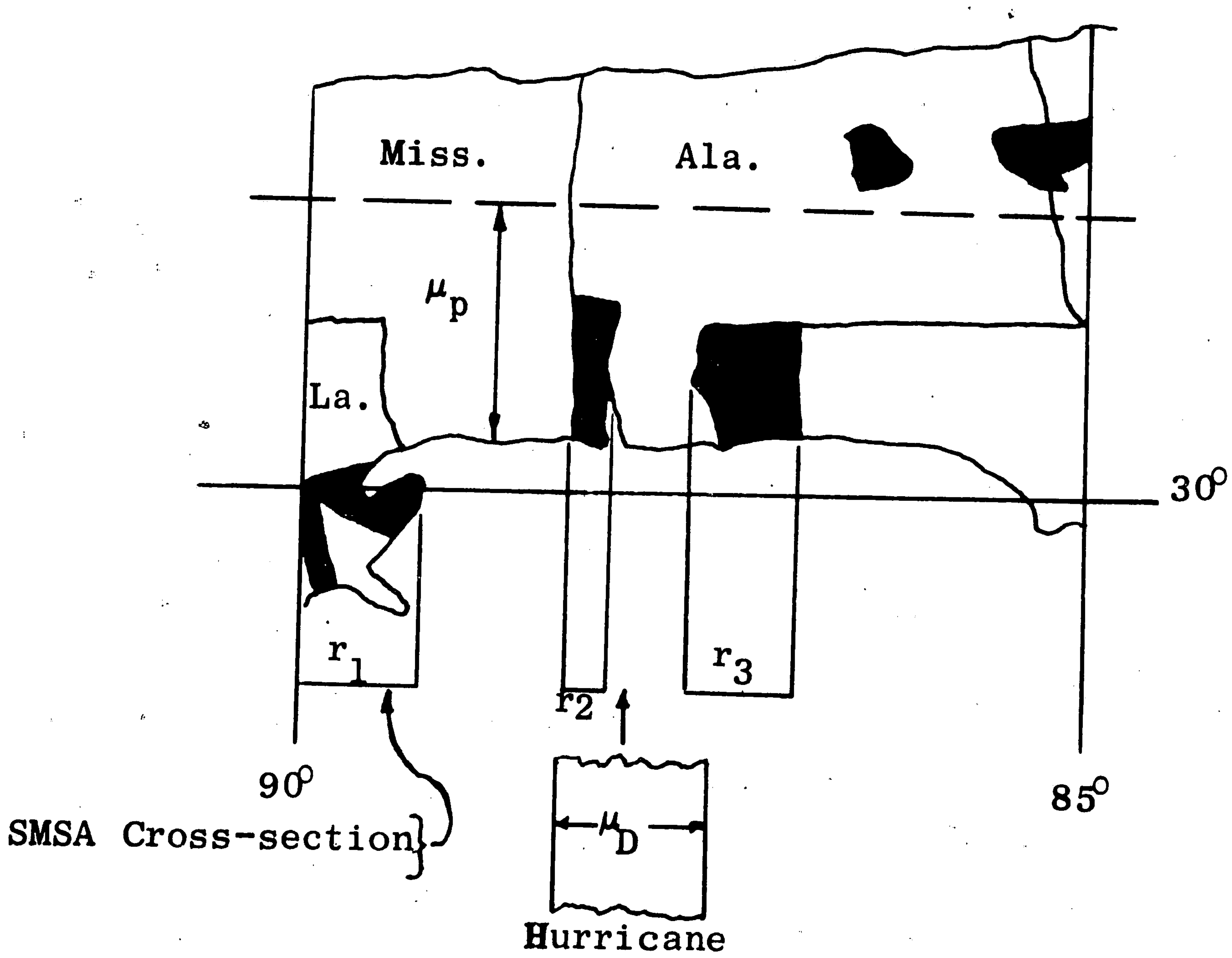

Figure 3 (Zone 3, SMSA's shaded)

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* A SMSA is a county or group of contiguous counties which contains at least one central city of 50,000 inhabitants or more or "twin cities" with a combined population of at least 50,000. In addition to the county, or counties, containing such a city or cities, contiguous counties are included in a SMSA if, according to certain criteria, they are essentially metropolitan in character and are socially and economically integrated with the central city.

Figure 3 shows the geographical area included in zone 3 ~~with~~ the SMSA's shaded.

The following assumptions will be made in the derivation of the SMSA probabilities:

1. A hurricane will cross into a zone perpendicular to the generalized coastline of a zone as shown in Figure 3.
2. The diameter of the hurricane will be the mean of the diameter distribution (μ_D).
3. The SMSA's in the path of the hurricane will be those in geographical area defined by the zone boundaries and the mean of the depth of penetration distribution (μ_D).
4. A hurricane has an equal probability crossing the zone coastline at any point on the coastline.
5. A hurricane is said to cross as SMSA when at least the radius of a nurricane covers the SMSA area.

The following procedure is then used to calculate the SMSA hurricane probability:

1. Find the value for μ_P for the area in question.
2. Determine the SMSA's in the area defined by μ_P and the parallels perpendicular to μ_P. This area is shown in Figure 3.
3. Determine the cross section of SMSA's within this area. The cross section for each SMSA (in miles) is shown in Figure 4 and is denoted r_1, r_2, r_3. The total cross

section will then be

$$\text{TOTAL CROSS SECTION} = \sum_i r_i$$

and for this case i = 1, 2, 3.

4. Calculate the probability that a hurricane will not pass through a SMSA; this probability is denoted $\overline{P}_{(SM)}$ and

$$P_{(SM)} = 1 - \overline{P}_{(SM)}$$

where
$$\overline{P}_{(SM)} = \frac{\sum_i \overline{d}_{(SM)i}}{\text{zone width}}$$

and $\sum_i \overline{d}_{(SM)i}$ denotes the sum of the distances on the SMSA cross section where a passage of the center of a hurricane will not result in the hurricane passing through a SMSA area.

The calculation of $\overline{P}_{(SM)}$ is performed as indicated in the following example:

As will be shown later for zone 3

μ_P = 88 miles (includes SMSA's shown on Fig. 3)

μ_D = 69 miles

From the SMSA map and Figures 3 and 4

r_1 = 60 miles

r_2 = 20 "

r_3 = 45 "

Zone Width = 310 miles

For this example, the SMSA cross section is expanded as shown in Figure 4.

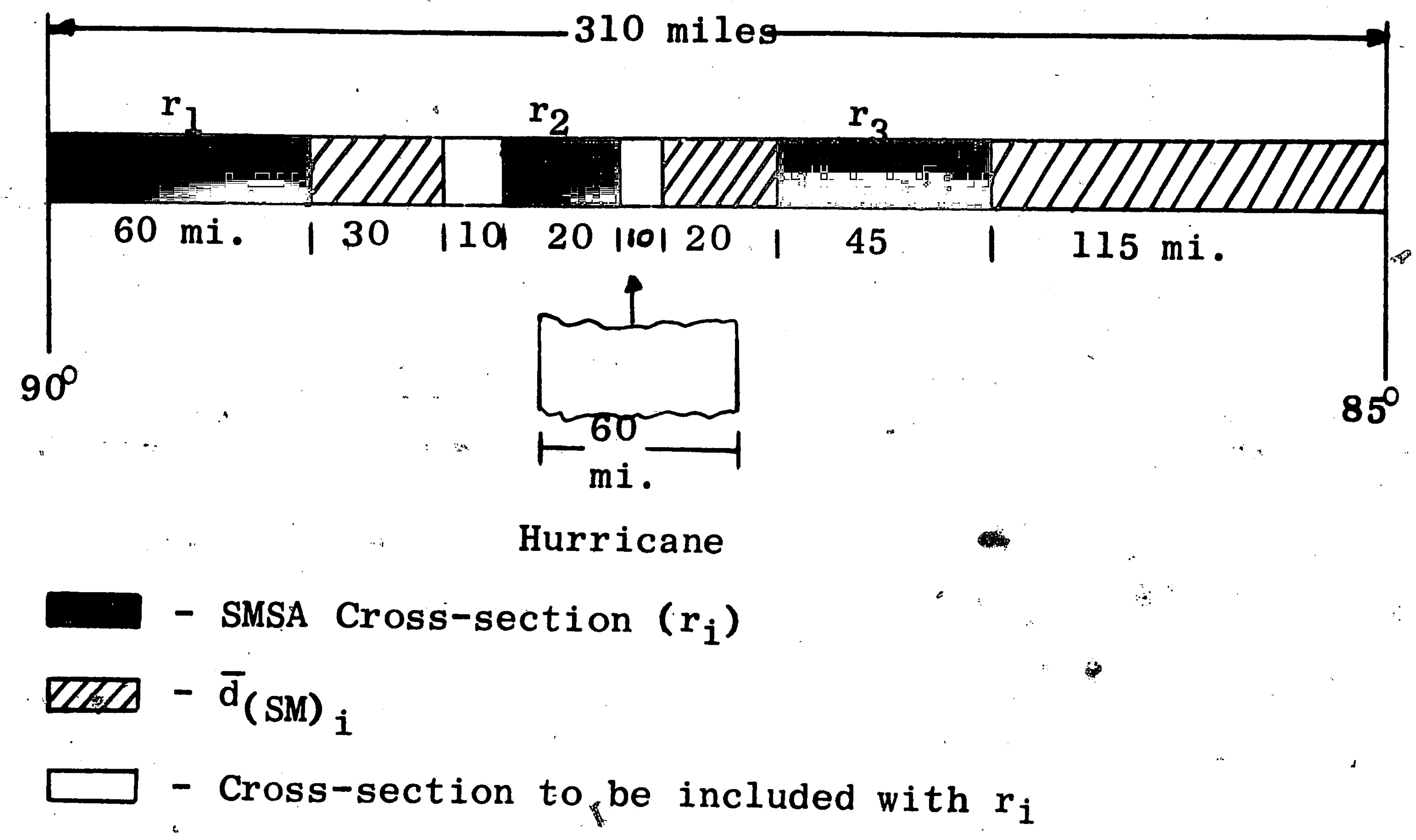


Figure 4.

Expanded Cross Section, Zone 3

From Figure 4,

$$\bar{P}_{(SM)} = \frac{\sum \bar{d}_{(SM)i}}{\text{zone width}}$$

$$= \frac{30 + 20 + 115}{310}$$

$$= \frac{165}{310}$$

$$\bar{P}_{(SM)} = .53$$

And finally, $P_{(SM)} = 1 - .53 = .47$ for zone 3 in any month.

No general expression can be derived for the SMSA probabilities due to the variance in the SMSA cross section from zone to zone. The SMSA hurricane passage probabilities can be found, in the same manner, for all zones.

Before leaving this section, a few words about the assumptions made in deriving the SMSA probabilities are in order. It is felt that the restrictions placed on how a hurricane enters a zone are generally valid. If one observes a map of the Southern United States with all hurricane crossings shown it will be noted that most hurricanes cross perpendicular to the generalized coastline. The use of average hurricane penetration and diameter may be somewhat conservative and it is left to the discretion of the user as to what values to use for application. The assumption that a hurricane has an equal probability of crossing the zone coastline at any point on the coastline is in general contradiction to the literature. However, due to insufficient data and the variability inherent in hurricane tracks it is felt that one cannot discern between two points within a zone and say that they have different probabilities of a hurricane crossing. It has been shown by Cleveland[10] that the mean 48 hour prognostication error in predicting the path of a hurricane is 55 miles with a standard deviation of 136 miles. If one cannot predict within 55 miles on the average, the path of a hurricane for a 48 hour time span, then one cannot state with any confidence that a hurricane crossing the zone next year is more likely at one point in a zone than another point in the same zone where the zone width is only 300 miles on the average. Finally, the assumption requiring that at least the radius cover the SMSA to constitute a crossing is arbitrary.

VII. HURRICANE VARIABLES (General)

Hurricanes (or tropical cyclones) have many variables in which a hurricane researcher can describe a given hurricane. However, for the purpose of this study, only the following variables will be used.

1. Speed (rate of lateral translation) - This variable denotes the speed (in knots or mi/hr) of the center of a hurricane. The units of measure will be mi/hr in this paper. Speed is a function of the latitudinal position of a hurricane. A hurricane at Boston will have a greater rate of translation than a hurricane in Florida and will therefore cover a greater area in the same amount of time. Hurricanes in the Gulf of Mexico will be assumed to be independent of latitude, since the latitudinal variation of speed in the Gulf is small.
2. Diameter - Since hurricanes are cyclonic, they will tend to be circular and will therefore have a diameter which will be measured in miles. The true diameter of hurricanes, which ranges between 50-900 miles, will not be used in this study. The diameter referred to hereafter will be the distance between the 75 mi/hr wind speed points on a line drawn through the center of the hurricane perpendicular to the direction of translation of the hurricane eye, as shown in Figure 5. This definition of diameter is consistent with the definition of a hurricane given in Section (4.1). The 75 mi/hr diameter will be less than the true diameter, which is based on barometric pressures, and will range between 30-140 miles.

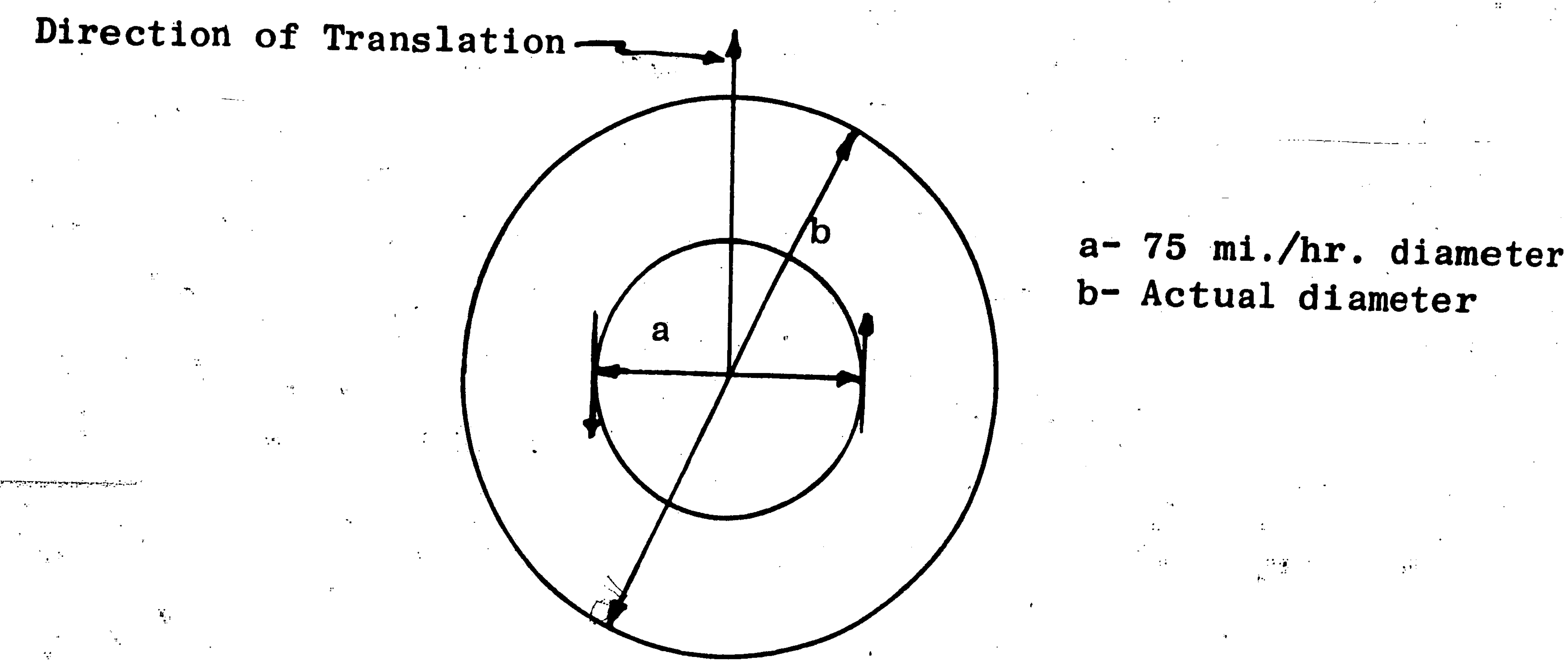


Figure 5
Relationship between 75 mi./hr. diameter and actual diameter.

3. Intensity - The measure of intensity used in this paper is the penetration of hurricane winds once a hurricane encounters the coastline, and it will be measured in miles. The measure of intensity used by the Weather Bureau is the Central Pressure Index (CPI) which is the barometric pressure and is measured in inches of mercury or millibars with 1 inch of mercury = 33.86 millibars. The CPI generally ranges between 32.00 and 26.00 inches of mercury, and it will be assumed that any value of CPI$\leq$29.40 is capable of sustaining 75 mi/hr hurricane winds required for a tropical cyclone by the hurricane definition. The CPI is related to wind speed, since it is a pressure gradient that creates a wind; this relationship will be discussed fully in Section (8.3).

These are the three variables which will be used in this study to determine the expected hurricane damage.

VIII. HURRICANE VARIABLES (Analysis)

This section will deal with statistical analysis of the data obtained for the hurricane variables; namely, speed, diameter, and intensity. The data will be presented and summarized for all six zones and a step-by-step analysis will be presented for zone six. The method of analysis described for zone six will be generally applicable for all zones.

8.1 Speed

It has been shown[5] that the forward speed of a hurricane is a function only of the latitudinal position of the hurricane and is therefore independent of all hurricane variables. For this study, it will be assumed that the forward speed will be constant for all zones although there exists a 5^{o} variation in latitude between zones. Since the difference in speed is relatively small for a latitudinal variation south of Cape Hatteras it is felt that this assumption is justified and will introduce very little error.

The data for all zones is summerized in Table XV in the Appendix.

8.1.1 Speed Data Analysis (Zone 6)

From the data for zone 6 the following frequency table was derived:

TABLE VI

Relative Frequency, Speed (Zone 6)

Speed (mi/hr) S_6	Relative Frequency	Emperical Cum. Prob. $F(S_6)$	Theoretical Cum. Prob. $G(S_6)$	Δ_6 $\lvert G(S_6)-F(S_6)\rvert$
0 - 7.5	3	.188	.075	.113
7.51 - 10.0	2	.313	.286	.027
10.1 - 12.5	4	.563	.606	.043
12.51 - 15.0	5	.876	.818	.058
15.1 - 17.5	1	.938	.931	.007
17.51 - 20.0	1	1.000	.978	.022

From Table VI, the mean and variance were estimated as

$$\mu_{S_6} = 12$$

$$\sigma^2_{S_6} = 12$$

It was then hypothesized that the sample for S_6 came from a Gamma distribution with mean μ_{S_6} and variance $\sigma^2_{S_6}$. This hypothesis was tested at the 5% significance level using the Kolmogorov-Smirnov Test. This test was performed in the following manner:

1. The cumulative theoretical distribution function for a Gamma distribution (mean - μ_{S_6}, Var. = $\sigma^2_{S_6}$) was tabulated(6) as $G(S_6)$ shown in Table VI.
2. The sample (c.d.f., $F(S_6)$, was tabulated as shown in Table VI.
3. The maximum deviation, Δ_6, defined by

$$\Delta_6 = \text{MAX} \; |G(S_6) - F(S_6)|$$

was found.

4. For the chosen significance level, if Δ is greater than or equal to a critical value, the hypothesis will be rejected.

The results for the zone 6 speed data are as follows:

$$\Delta_6 = |.075 - .188| = .113$$

$\Delta(\text{critical}) = .328$ for a sample size of 16 at the 5% level

Since $\Delta_6 < \Delta(\text{critical})$, we cannot reject the hypothesis that the sample for S_6 came from a Gamma distribution.

Therefore for zone six:

$$F(S_6) = \frac{(S_6)^{11} e^{-S_6/12}}{\Gamma(a+1) b^{a+1}} \quad \text{where} \quad \begin{aligned} b\,(a+1) &= \mu_{S_6} \\ b^2 (a+1) &= \sigma_{S_6}^2 \end{aligned}$$

From the sample data

$\mu_{S_6} = 12.$

$\sigma_{S_6}^2 = 12.$

and

$a = 11.$

$b = 12.$

Finally

$$F(S_6) = \frac{S_6^{11} e^{-S_6/12}}{\Gamma(12)(12)^{12}} \quad \text{for} \quad S_6 \geq 0$$

The results of the analysis of the speed data for the other zones is summarized in Table (IX).

8.2 Diameter

The diameter data for all zones is shown in Table XVI in the Appendix. It has been hypothesized(6) that the diameter is dependent on the Central Pressure Index (CPI). This dependence will be investigated, on a statistical basis, in this section. The need for this investigating dependence is necessary since independence among the hurricane variables is required in the damage model. Along with this investigation an analysis of diameter similar to that conducted for speed, in the previous section, will be performed on the data.

8.2.1 Diameter Data Analysis (Zone 6)

From the data for zone six the following frequency table was derived.

TABLE VII

Frequency Table - Diameter - Zone 6

Diameter(miles)	Relative	Empirical Cum. Prob.	Gamma Theoretical Cum. Prob.	Δ_6
D_6	Frequency	$F(D_6)$	$G(D_6)$	$\lvert G(D_6)-F(D_6)\rvert$
0 - 20	1	.059	.001	.058
21 - 40	3	.236	.102	.134
41 - 660	7	.646	.410	.236
61 - 80	3	.823	.708	.105
81 - 100	2	.941	.888	.053
101 - 120	0	.941	.962	.021
121 - 140	1	1.00	.989	.011

From Table (VII), the mean and variance for D_6 were estimated as

$$\mu_{S_6} = 58$$

$$\sigma_{D_6}^2 = 638$$

It was hypothesized that the sample for D_6 came from a Gamma distribution with mean $\mu_{D_6}^2$ and variance $\sigma_{D_6}^2$. Testing this hypothesis at the 5% level using the Kolmogorov-Smirnov test as before yielded the following results:

$$\Delta_6 = \text{MAX } |G(D_6)-F(D_6)|$$

$$= |.410 - .646|$$

$$= .236$$

$$\Delta_{(\text{critical})} = .318$$ for a sample size of 17 at the 5% level

Since $\Delta_6 < \Delta(\text{critical})$, we cannot reject the hypothesis that the sample for D_6 came from the hypothesized Gamma distribution. Therefore, for zone six:

$$f(D_6) = \frac{D_6^{\,d}\, e^{-D_6/f}}{\Gamma(d+1)f^{d+1}}$$

where $f(d+1) = \mu_{D_6}$

$d^2(d+1) = \sigma_{D_6}^2$

From the sample data

$$\mu_{D_6} = 58$$

$$\sigma_{D_6}^2 = 638$$

and

$$d = 4.4$$

$$f = 10.8$$

Finally

$$f(D_6) = \frac{D_6^{\,4.4}\, e^{-D_6/10.8}}{\Gamma(5.4)(10.8)^{5.4}}$$ for $D_6 \geq 0$

8.2.2 Diameter and CPI (Independence Test), Zone 6

Finally to investigate the dependence between the diameter and the Central Pressure Index, the following procedure was used.

1. The hypothesis (Ho) was made that C_6 and D_6 were independent, where C_6 is the observed Central Pressure Index for zone 6. The paired data for C_6, D_6 is shown in the appendix for all zones.

2. To test the hypothesis (H_0), a corner test[8] was performed at the 95% significance level. This test was chosen since it appears, although not proven, to be the test which is most likely to reject the null hypothesis H_0 if it is false.

3. The data for C_6 and D_6 was plotted as shown in Figure 6.

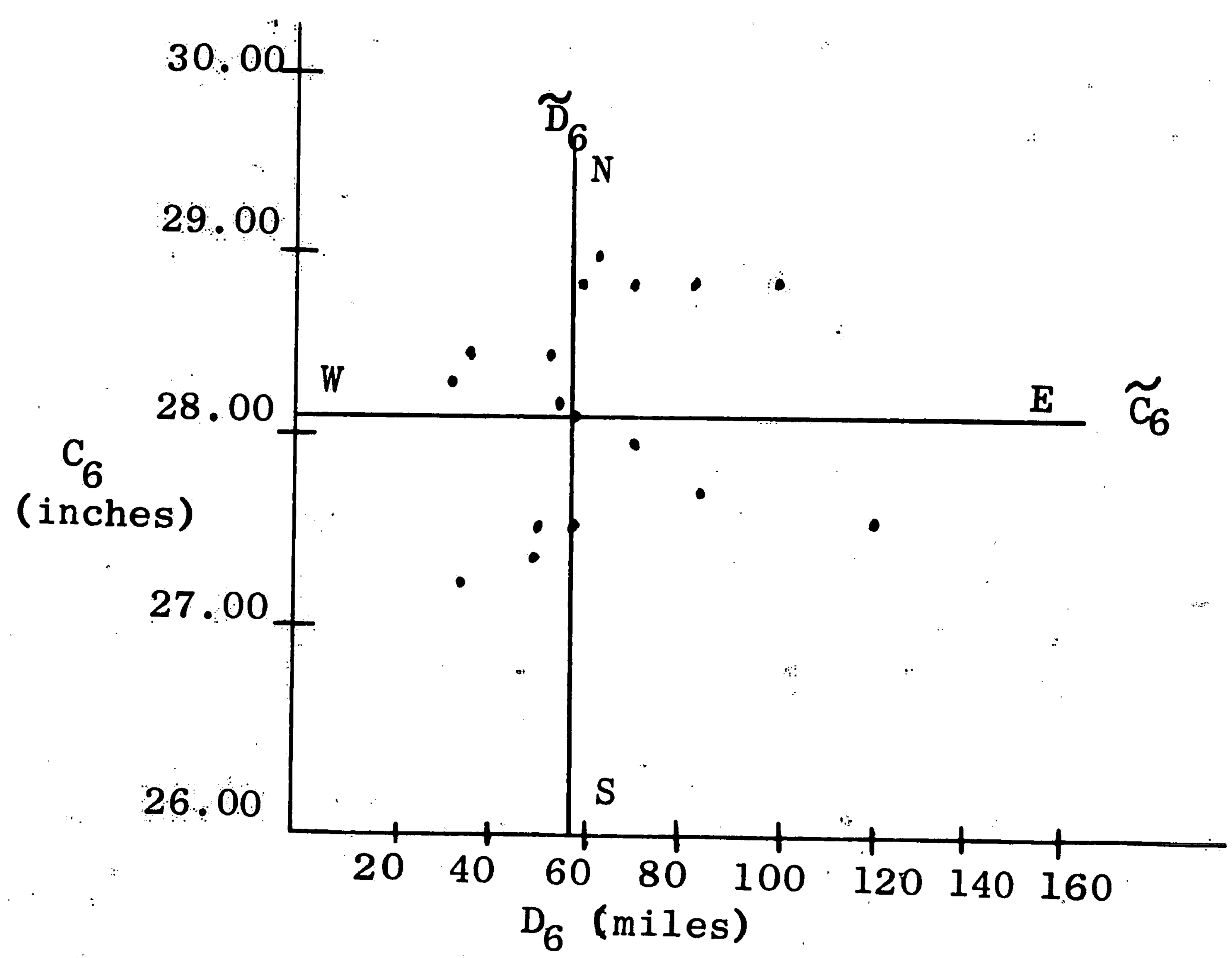


Figure 6. C_6 vs. D_6, Partitioned

4. The graph in Figure 6 was then partitioned by $\tilde{C}_6$ and $\tilde{D}_6$ the medians of C_6 and D_6 where $\tilde{C}_6$ = 28.10 inches

$\tilde{D}_6$ = 55.2 miles

From Figure 6 it was found that

$$K_T = K_N + K_E + K_W + K_S$$

$$= 5 + 0 + 1 + 3\tfrac{1}{2}$$

or $$K_T = 9\tfrac{1}{2}.$$

The decision rule used in the corner test is

Reject Ho if $K_T > K$ critical.

From a corner table with n=17, ϵ =.05 it was found that

$$K_{critical} = 11$$

and since

$$K_T < K \text{ critical}$$

we cannot reject the independence hypothesis Ho. Therefore on a statistical basis it can be concluded that C_6 and D_6 are independent and this assumption shall be maintained throughout this paper.

8.3 Intensity

The intensity criterion used by the Weather Bureau is the Central Pressure Index. For this study, it was concluded that the CPI is not a good criterion for intensity since it does not relate directly to hurricane damage. It was decided to find a factor which is a function of CPI and relates directly to hurricane damage and this factor is the depth of penetration of hurricane winds when a hurricane encounters a land mass. The penetration will be calculated by multiplying the speed of a hurricane (in miles/hours) by the time (in hours) for the hurricane winds to fall to the 75 mile/hour velocity or for the CPI to rise to 29.40 inches. In the notation of this paper, the penetration is written as

$$(\text{PENETRATION})_i = S_i T_i \text{ for zone i.} \qquad (8\text{-}1)$$

However equation (8-1) is valid only for zones one through five since a hurricane encountering Flordia (Zone 6) will transverse the entire width of the state which requires that S_6T_6 is constant and takes on a value equal to the average width of the state or 140 miles. Therefore

$$(\text{PENETRATION})_i = S_i T_i \quad \text{for } i = 1,2,3,4,5$$

$$\text{and } (\text{PENETRATION})_6 = 140 \text{ miles.}$$

Since the speed (S_i) is known, the only remaining variable to define and analyze is T_i where T_i is a function of C_i, as will be shown in section 8.3.2. Before the relationship between T_i and C_i is investigated, the data for C_i will be analyzed.

8.3.1 CPI Analysis

Since the CPI data ranges between 26.00 and 29.40 inches, a transformation is necessary to transform the data into more usable form. This transformation yields a new variable C_6^1, for zone 6, where

$$C_6^1 = \frac{C6 - 26.00}{29.40-26.00}$$

or

$$C_6^1 = \frac{C6 - 26.00}{3.40} \qquad (8\text{-}2)$$

which yields

$$0 \leq C_6^1 \leq 1$$

when $$26.00 \leq C_6 \leq 29.40$$

In zone 6, since C_6^1 ranges between 0 and 1, it was hypothesized that the sample for C_6^1 came from a Beta distribution of the form

$$f(C_6^1) = \frac{1}{B(g,h)} (C_6^1)^g (1-C_6^1)^h \tag{8-3}$$

with mean μ_{C_6} and variance $\sigma^2_{C_6}$. The sample data for C_6^1 was formed into the frequency table and from this table it was found that

$$\mu_{C_6^1} = .852$$

$$\sigma^2_{C_6^1} = .028$$

The parameters g and h were calculated from the following equations

$$\frac{g+1}{g+h+2} = \mu_{C_6^1} = .852 \tag{8-4}$$

$$\frac{(g+1)(h+1)}{(g+h+2)^2(g+h+3)} = \sigma^2_{C_6^1} = .028 \tag{8-5}$$

which yields

$$g = 2$$

$$h = -.5.$$

The hypothesis was then tested using the Kolmogorov-Smirnov test at the 95% level with a simple size of 100 with the following results

$$\Delta_6 = \text{MAX} \left| G(C_6^1) - F(C_6^1) \right|$$

$$= .400 - .344 = .056$$

and $$\Delta_{\text{Critical}} = \frac{1.36}{100} = .136$$

Since $\Delta_6 < \Delta critical$, the hypothesis that C_6^1 came from the hypothesized Beta distribution cannot be rejected at the 95% level.

Therefore

$$f(C_6^1) = \frac{1}{B(2,-\frac{1}{2})} (C_6^1)^2 (1-C_6^1)^{-\frac{1}{2}} \text{ for } 0 \le C_6^1 < 1$$

and in general

$$f(C_i^1) = \frac{1}{B(a,b)} (C_i^1)^a (1-C_i^1)^b \text{ for } 0 \le C_i^1 \le 1 \tag{8-6}$$

The results of the analysis for all other zones is shown in Table IX.

8.3.2 Time and CPI

The fundamental relationship to be used to relate CPI and time comes from an empirical analysis(5) on the reduction of wind speeds as a hurricane transverses a land mass. From this analysis an adjustment ratio was derived and is shown in Table VIII, which can be applied to the coastal wind speed to determine the expected wind speed t hours later. This adjustment ratio will be denoted as r and is constant for all zones except zone 6 where it is not required.

Time(hrs.)	Adjustment Ratio (r)
t (at the coast)	1.00
t+1	.93
t+2	.88
t+3	.85
t+4	.82
t+5	.80
t+6	.78
t+7	.76
t+8	.74

Table VIII

Factors For Reducing Wind Speeds When Center Over Land

For example, if the wind speed at the coast was 100 miles/hr, the expected wind speed 1 hour later = 93 mi/hr, 2 hours later = 88 mi/hr, 3 hours later = 85 mi/hr, etc.

Since there exists a relationship between time and the adjustment ratio, the problem narrows down to relating CPI and the adjustment ratio. From Table VIII it was found that

$$r = e^{-.05T_i}$$

or

$$T_i = -20 \ln r \quad \text{where } 0 < r < 1 \qquad (8\text{-}7)$$

From the defination of a hurricane presented in Section (IV) (Wind speed $\geq$ 75 mi/hr or CPI $\leq$ 29.40) the following relationship can be written at the time of maximum penetration,

$$r = \frac{75}{WS_c} \qquad (8\text{-}8)$$

where WS_c denotes the wind speed at the coast. Substituting

$r = \frac{75}{WS_c}$ in equation (8-7) yields

$$T_i = -20 \ln \left(\frac{75}{WS_c}\right) \qquad (8\text{-}9)$$

From empirical of CPI vs wind speed it has been shown that(5)

$$WS_c = 75\sqrt{29.90 - C_i} \qquad \text{for zone } i, \quad i = 1,2,3,4,5,6 \qquad (8\text{-}10)$$

where 29.90 is the asymptotic barometric pressure. Substituting C_i^1 for C_i and then substituting for WS_c in equation (8-9) yields

$$T_i = -20 \ln \frac{1}{\sqrt{3.9 - 3.4\, C_i{}^1}} \qquad (8\text{-}11)$$

Equation (8-11) then expressed T_i in terms of C_i^1 which is the required result but the equation is not consistent since T_i becomes negative for $C_i^1 \geq .853$. Since approximately 50% of the values for C_i^1 are greater than .853, this relationship is not valid. A plot of equation (8-11) is shown in Figure (7).

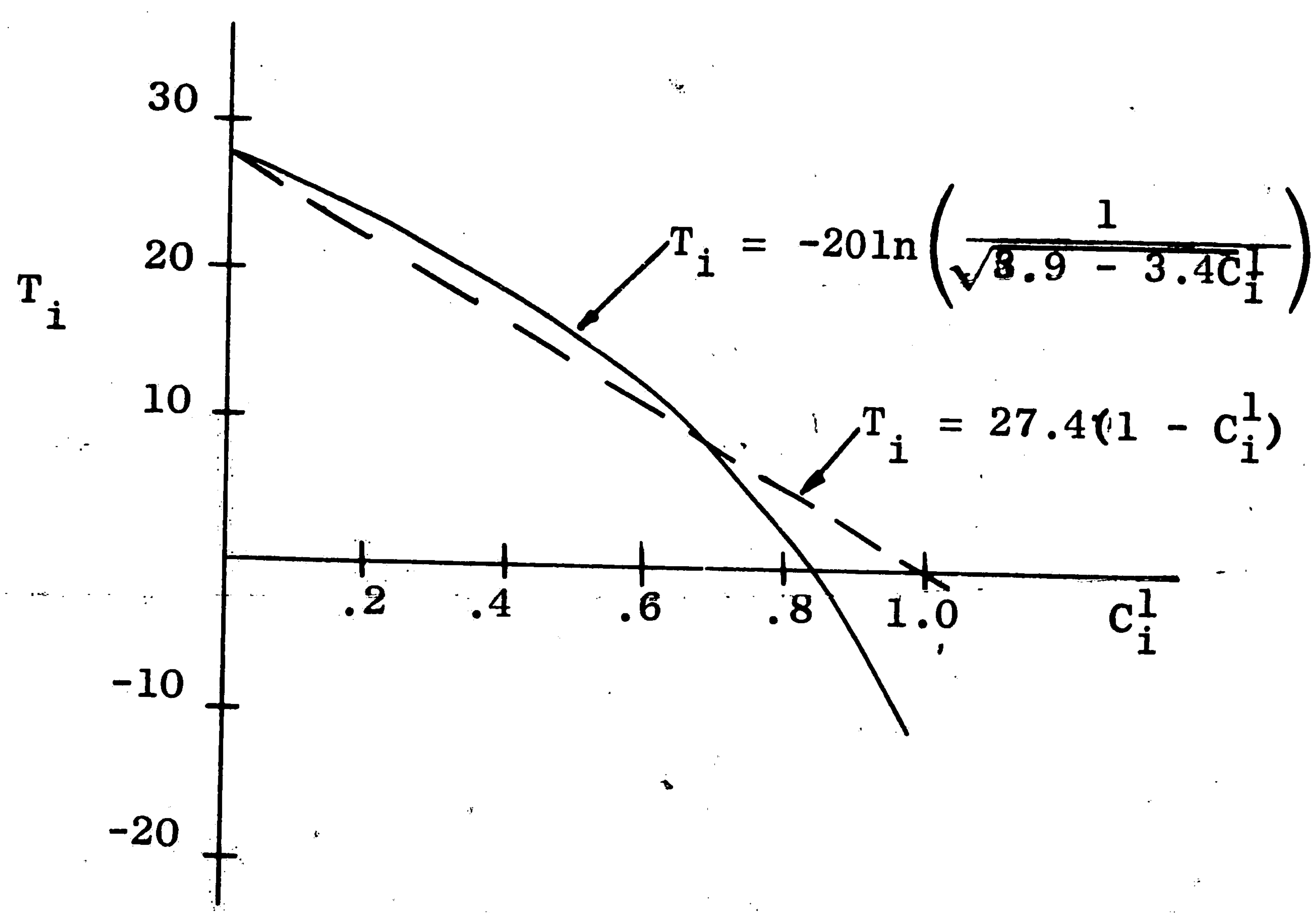


Figure 7. T_i vs. C_i^1

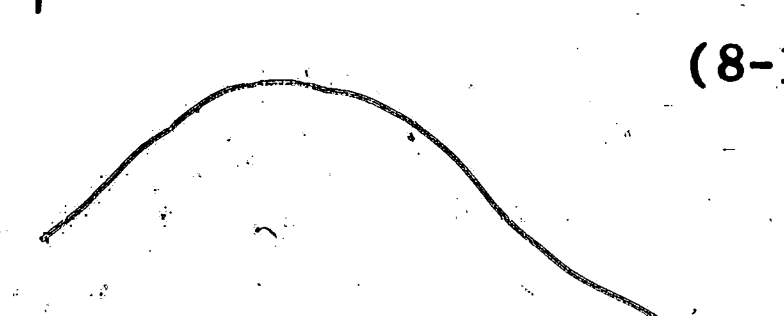
As shown in Figure (7) an approximation to equation (8-11) was made by the straight line (dashed line) passing through (27.4,0) and (0,1). Using this line the relationship between C_i^1 and T_i becomes.

$$T_i = 27.4\ (1 - C_i^1) \tag{8-12}$$

and it is relationship which will be used as an approximation to equation (8-11) to relate time and CPI.

To find the distribution for T_i, the following change of variable was made.

$$g(T_i) = \begin{cases} f(C_i^1)\ \left|\dfrac{d(C_i^1)}{dT_i}\right| & \text{for } 0 \leq T_i < 27.4 \\ 0 \text{ elsewhere} & \end{cases} \tag{8-13}$$



where $f(C_i^1) = \frac{1}{B(a,b)} (C_i^1)^a (1-C_i^1)^b$ for $0 < C_i^1 < 1$

$$C_i^1 = 1 - \frac{T_i}{27.4}$$

and $$\frac{dC_i^1}{dT_i} = \frac{-1}{27.4}$$

which yields

$$g(T_i) = \frac{1}{27.4\ B(a,b)} \left(1 - \frac{T_i}{27.4}\right)^a \left(\frac{T_i}{27.4}\right)^b \quad \text{for} \quad 0 < T_i < 27.4 \tag{8-14}$$

Equation (8-14) is then the density function for the time until a hurricane reaches the maximum penetration where the wind speed decreases to 75 mi/hr or the CPI increases to 29.40 inches. The variable T_i has a mean μ_{T_i} and $\sigma_{T_i}^2$ where

$$\mu_{T_i} = E(T_i) \tag{8-15}$$

where
$$T_i = 27.4\,(1-C_i^1)$$

Substitution yields

$$\mu_{T_i} = E(27.4(1-C_i^1)$$

$$= 27.4\left[1 - E(C_i^1)\right]$$

$$\mu_{T_i} = 27.4\left[1 - \mu_{C_i^1}\right] \tag{8-16}$$

and $$\sigma_{T_i}^2 = E(T_i^2) - \left[E(T_i)\right]^2$$

or
$$= E\left[27.4^2\,(1-C_i^1)^2\right] - \mu_{T_i}^2 \tag{8-17}$$

Expanding (8-17) and collecting terms yields

$$\sigma_{T_i}^2 = 27.4^2 \left[E(C_i^1)^2 - \mu_{C_i}^2 \right]$$

or $\sigma_{T_i}^2 = 750\ \sigma_{C_i}^2$ (8-18)

Since μ_{Ci} and $\sigma_{C_i}^2$ are known, μ_{T_i} and $\sigma_{T_i}^2$ can be determined and are summerized on Table IX.

8.4 Hurricane Variable Analysis Summary

The following table is a summary of the results of the hurricane variable analysis. All parameters are estimated from sample data.

	D_i DIAMETER (mi.)	S_i SPEED (mi/hr)	C_i TRANSFORMED CPI	T_i TIME (hrs)
ZONE ONE	GAMMA* Mean = 46.0 Var. = 274. a = 6.7 b = 6.0	GAMMA* Mean = 12.0 Var. = 12.0 a = 11.0 b = 12.0	BETA** Mean = .809 Var. = .028 a = 2.7 b = -.1	TRANSFORMED BETA*** Mean = 5.2 Var. = 30.8 a = 2.7 b = -.1
ZONE TWO	GAMMA Mean = 60 Var. = 1190 a = 2.0 b = 20.0	GAMMA Same As Zone One	BETA Mean = .812 Var. = .022 a = 3.8 b = .1	TRANSFORMED BETA Mean = Var. 30.8 a = 3.8 b = .1
ZONE THREE	GAMMA Mean = 69.0 Var. = 1840 a = 1.6 b = 27.0	GAMMA Same As Zone One	BETA Mean = .838 Var. = .016 a = 5.3 b = .2	TRANSFORMED BETA Mean = 4.4 Var. = 13.2 a = 4.3 b = .2
ZONE FOUR	GAMMA Mean = 62.0 Var. = 900. a = 3.3 b = 14.5	GAMMA Same As Zone One	BETA Mean = .910 Var. = .012 a = 4.3 b = .5	TRANSFORMED BETA Mean = 5.7 Var. = 16.7 a = 4.3 b = .5
ZONE FIVE	GAMMA Same As Zone Four	GAMMA Same As Zone One	BETA Same As Zone Four	TRANSFORMED BETA Same As Zone Four
ZONE SIX	GAMMA Mean = 58.0 Var. = 638. a = 4.3 b = 11.0	GAMMA Same As Zone One	BETA Mean = .852 Var. = .028 a = 2.0 b = -.5	TRANSFORMED BETA Mean = 6.2 Var. = 26.2 a = 2.0 b = -.5

$$* \; f(X) = \frac{X^a e^{-X/b}}{\Gamma(a+1)\, b^{a+1}}$$

$$** \; f(X) = \frac{(a+b+2) X^a (1-X)^b}{\Gamma(a+1)\Gamma(b+1)}$$

$$*** \; f(X) = \frac{(a+b+2)\left[1-\frac{X}{27.4}\right]^a \left[\frac{X}{27.4}\right]^b}{(27.4)\,\Gamma(a+1)\Gamma(b+1)}$$

Table IX (Hurricane Variable Summary)

IX DAMAGE MODEL (Theoretical Development)

9.1 General

Deriving a model for damage based on engineering concepts is a complex and perhaps impossible task. Each product or facility has its own unique damage characteristics with respect to hurricane winds and the number of variables becomes unmanageable even for the simplest of cases. Some of the variables which should be considered for an engineering model are:

1. Wind stress
2. Product cross-sectional area
3. Product hardness to wind
4. Variation of wind stress across the diameter of a hurricane.
5. Salt air and water damage
6. Hurricane size
7. Hurricane speed
8. Product density
9. Design level of product against wind
10. Product age

As can be seen from the above list, designing a model to include these variables (and more) is a complex task. One other compelling need for a simple model is that very little data can be gathered together to form an engineering model, and the gathering of data (if it were available) would be a complex and expensive task.

The desired damage model is one which has the following characteristics:

1. Easily applied
2. Based on data which is readily accessible
3. Universal in scope (applies equally well to all zones and months
4. Reasonably accurate
5. Smoothes the variability associated with hurricanes (due to the variability associated with the high energy release per time period of a hurricane, it becomes necessary to filter the high frequency random components to glean any useful information on the expected damage level of a hurricane.)

With these characteristics in mind, the following model for damage is presented.

9.2 Damage Model (Zone i)

The damage model is:

$$X_i = A_i R_i^{\alpha}$$

where X_i = estimated level of damage is zone i (units)

A_i = estimated land mass area which will be covered by hurricane winds in zone i (miles^2)

R_i = product density in zone i $\frac{\text{units}}{\text{miles}^2}$

α = a constant (to be determined).

In this model the product density (R_i) is raised to the α power to account for the fact that a certain amount of the product is hardened to hurricane damage, where $0 \leq \alpha \leq 1$.* The area (A_i) is that defined

* For further discussion of α , see Appendix II.

by the expected depth of penetration and the expected diameter as shown in Figure (8).

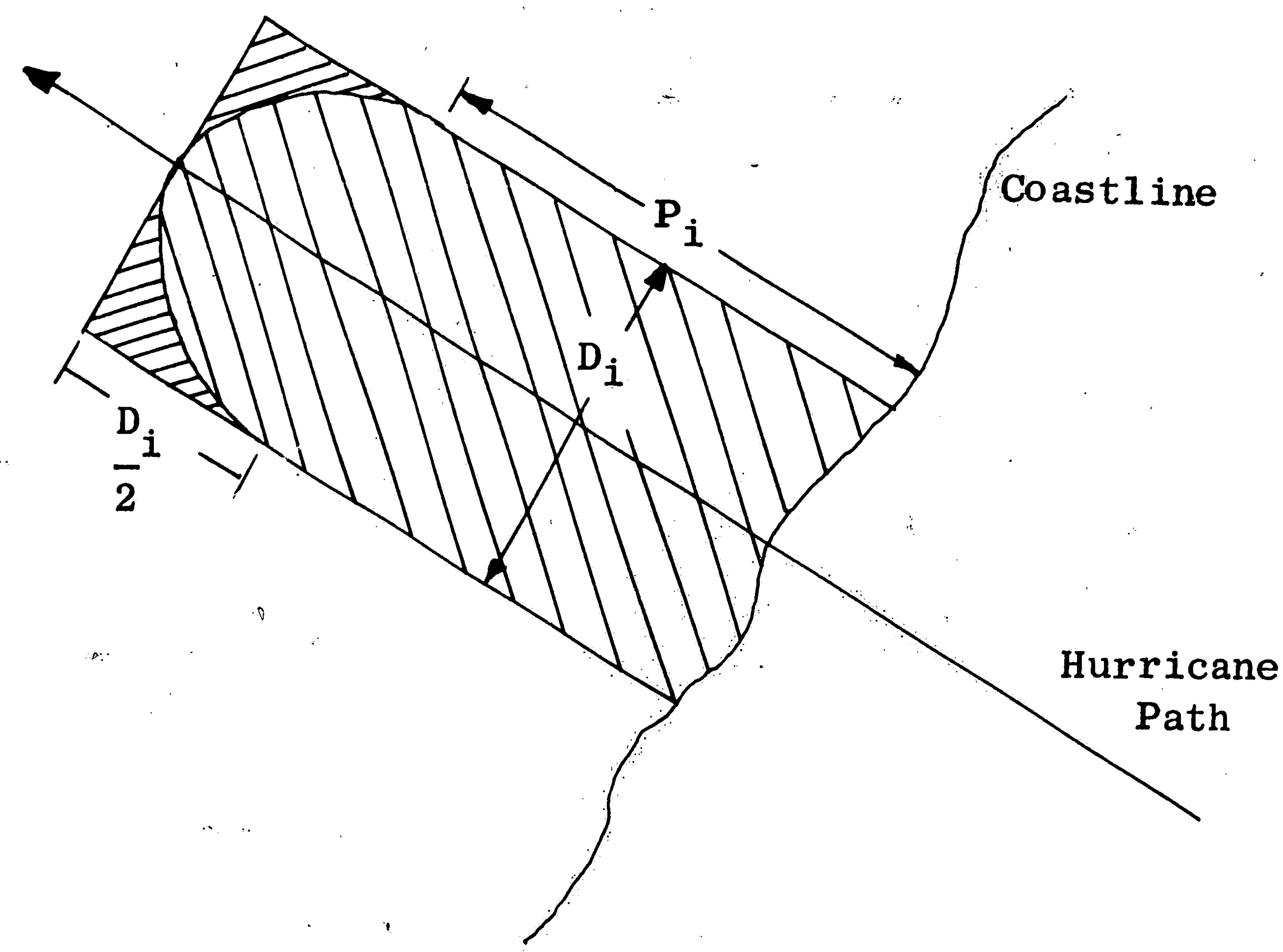


Figure 8. Hurricane Areal Coverage Diagram

The shaded area in Figure (8) is the area (A_i) in the model; the area defined by the semi-circle is necessary since the maximum penetration is defined at the center of the hurricane.

From Figure (8), the area is defined as

$$A_i = D_i P_i + D_i^2/2 \tag{9-2}$$

where the semi-circle is taken as a $D_i/2$ x D_i rectangle, or

$$A_i = D_i \left[P_i + D_i/2 \right] \tag{9-3}$$

From section (VIII)

$$P_i = S_i T_i$$

which yields (after substitution)

$$A_i = D_i \left[S_iT_i + \frac{D_i}{2}\right]$$

finally, the model becomes

$$X_i = D_iR_i^{\alpha}\left[S_iT_i + \frac{D_i}{2}\right] \qquad (9\text{-}4)$$

The analysis and the characteristics of the variables D_i, S_i, and T_i is found in section (VIII), and the remaining variable R_i^{α} and the constant α must be found before X_i can be calculated.

9.3 Theoretical Damage Model Analysis (Zone i)

Again, from equation (9-4), the damage model is

$$X_i = D_iR_i^{\alpha}\left[S_iT_i + \frac{D_i}{2}\right]$$

or

$$X_i = D_iS_iT_iR_i^{\alpha} + \frac{D_i^{2}R_i^{\alpha}}{2}$$

As shown previously, D_i, S_i and T_i are independent, and it is assumed that R_i^{α} is independent of D_i, S_i and T_i. Since D_i, S_i, T_i and R_i^{α} are all random variables, then X_i is a random variable with mean μ_{X_i} and variance $\sigma^2_{X_i}$ where

$$\mu_{X_i} = E(X_i) = E\left[D_iS_iT_iR_i^{\alpha} + \frac{D_i^{2}R_i^{\alpha}}{2}\right]$$

$$= E(D_i)\,E(S_i)\,E(T_i)\,E(R_i) + \tfrac{1}{2}E(D_i^2)\,E(R_i^{\alpha})$$

since $E(D_i^2) = \sigma_{D_i}^2 + \mu_{D_i}^2$

then

$$\mu_{X_i} = \mu_{D_i}\mu_{S_i}\mu_{T_i}\mu_{R_i^{\alpha}} + \frac{\mu_{R_i^{\alpha}}}{2}(\sigma_{D_i}^2 + \mu_{D_i}^2) \qquad (9\text{-}5)$$

and $$\sigma_{X_i}^2 = E(X_i^2) - [E(X_i)]^2$$

or

$$\sigma_{X_i}^2 = E(X_i^2) - \mu_{X_i}^2 \qquad (9\text{-}6)$$

where $$E(X_i^2) = E\left(D_iS_iT_iR_i + \frac{D_i^2R_i^\alpha}{2}\right)^2$$

$$= E\left(D_i^2S_i^2T_i^2R_i^{2\alpha} + D_i^3R_i^{2\alpha}S_iT_i + \frac{D_i^4R_i^{\alpha 2}}{4}\right)$$

$$= E(D_i^2)\ E(S_i^2)\ E(T_i^2)\ E(R_i^\alpha)^2 + [E(D_i^3)\ E(R_i^\alpha)^2$$

$$E(S_i)\ E(T_i)] + \tfrac{1}{4}E(D_i^4)\ E(R_i^\alpha)^2$$

and $$E(D_i^2) = \sigma_{D_i}^2 + \mu_{D_i}^2$$

$$E(S_i^2) = \sigma_{S_i}^2 + \mu_{S_i}^2$$

$$E(T_i^2) = \sigma_{T_i}^2 + \mu_{T_i}^2$$

$$E(R_i)^2 = \sigma_{R_i^\alpha}^2 + \mu_{R_i^\alpha}^2$$

$$E(S_i) = \mu_{S_i}$$

$$E(T_i) = \mu_{T_i}$$

$$E(D_i^3) = \int_{-\infty}^{\infty} D_i^3\ f(D_i)\ dD_i$$

$$E(D_i^4) = \int_{-\infty}^{\infty} D_i^4\ f(D_i)\ dD_i$$

From equations (9-5) and (9-6) the mean and variance of the damage distribution can be found for zone i. However, knowing the mean and variance of X_i does not define the shape of distribution. The actual distribution of X_i can be found analytically by a four-stage change of variable process; however, this process yields unwieldly mathematics and will not be carried out in this paper. A simplier, less time consuming technique is to sample from the distributions for D_i, S_i, T_i, and R_i^α, calculate X_i for each $(D_i, S_i, T_i, R_i^\alpha)$, and then fit a distribution to the X_i sample. Since μ_{X_i} and $\sigma^2_{X_i}$ are known, the sample size required to determine the shape of the distribution can be relaxed a little. It was assumed that if one could be 95% confident that 95% of the population for X_i was included within the range of the random sample and if the sample mean and sample variance converged to within 10% of the population mean and variance respectively then one could be confident that the shape of the sample distribution is the shape of the distribution for the population. Based on this assumption and using Wilk's distribution free technique for sample size, at the (.05,.05) levels, it was found that a sample of size 93 would be required. However, this is only the minimum size required and convergence will determine the upper limit for the required sample size. The (X-Distribution) flowchart in the appendix describes the sampling technique used to find the distribution of X_i.

The sampling technique described above is simply stated as "sample from the X_i population until the sample mean and the true mean are within 10% of one another and until the sample variance and the true variance are within 10% of one another and the sample size is greater than 93." With the sample obtained from this technique we can state with some confidence that the shape of the sample distribution is that of the true distribution. This statement is based on the concept that the sample distribution will converge on the true distribution when the distribution parameters converge.

9.4 Damage Model (Southern United States)

At this point, the damage distribution is known for each zone along with their respective probabilities. It is now necessary to find the damage distribution for the entire area under study (Zone 1 through Zone 6) for one hurricane season. This damage will be denoted by Z, where

$$Z = Z_0 p(0) + Z_1 p(1) + Z_2 p(2) + \dots + Z_n p(n) \tag{9-7}$$

where

Z_j = damage due to jth hurricane

$p(j)$=probability of the occurrance of the jth hurricane

$j = o, 1, 2, \dots, n$

and $Z_0 = 0$

$$Zj = \sum_{i=1}^{6} X_i \, p(h_i) + \sum_{i=1}^{5} X_i \, p_2(h_i) \qquad j=1,2,\dots,n \tag{9-8}$$

where X_i = Zone i damage level

$p(h_i)$ = probability of a hurricane crossing zone i in one season.

$p_2(h_i)$= probability of two zone crossing, the second zone being i.

Expanding Equation (9-8) yields

$$Z_j = \sum_{i=1}^{6} a_i X_i \tag{9-9}$$

where $a_i = p(h_i) + p_2\ (h_i)$ for $i = 1,2,3,4,5$

$$a_6 = p(h_6) \tag{9-9a}$$

Substituting (9-9) into (9-7) yields for Z

$$Z = \sum_{j=1}^{n} p(j) \sum_{i=1}^{6} a_i X_i \tag{9-10}$$

Writing the density function for Z from equation (9-10) yields

$$f(Z) = \sum_{j=1}^{n} f\left(p(j) \sum_{i=1}^{6} a_i X_i \right) \tag{9-11}$$

In order to obtain f(Z) as a function of Z the function $f\left(p(j) \sum_{i=1}^{6} a_i X_i \right)$ must first be evaluated. From Table XI in Section (X):*

$$f(X_i) = \frac{1}{m_i} e^{-X_i/m_i} \qquad \text{for } i = 1,2,3,4,5^{**} \text{ and } m_i = \mu_{X_i} = E(X_i) \tag{9-12}$$

Now letting X_i in (9-12) equal $p(j)\ a_i X_i$ and making the indicated change of variable yields

$$f(p(j)\ a_i X_i) = \frac{1}{p(j)\ a_i m_i} e^{-\frac{X_i}{p(j)\ a_i m_i}} \tag{9-13}$$

for the jth hurricane in zone i for all i and j.

Substituting (9-13) into (9-11) yields for f(Z)

$$f(Z) = \sum_{j=1}^{n} \left[\sum_{i=1}^{5} \frac{1}{p(j) a_i m_i} e^{-X_i/p(j) a_i m_i} \right] \tag{9-14}$$

To write equation (9-14) as a function of Z rather than X_i requires a convolution of n x 5 terms which can be done as follows:

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* The $f(X_i)$ in equation (9-12) is a special case for the product used in this study, namely "number of telephone stations affected." The results may or may not be the same for any other product.

** Zones 4 and 5 have been grouped together and denoted as zone 4.

1. Write the moment function for equation (9-14) which yields

$$M_Z(t) = \frac{1}{\prod_{k=1}^{nx5} (1-p(k)a_k m_k t)} \tag{9-15}$$

2. Transform equation (9-15) to a Laplace transform by substituting S for -t or

$$f(S) = \frac{1}{\prod_{k=1}^{nx5} (1+p(k)a_k m_k S)}$$

or

$$f(S) = \frac{1}{p(k)a_k m_k \prod_{k=1}^{nx5} \left(S + \frac{1}{p(k)a_k m_k} \right)}$$

let $e_k = 1/p(k)a_k m_k$

yields

$$f(S) = \prod_{k=1}^{nx5} \frac{e_k}{S + e_k} \tag{9-16}$$

3. Expand equation (9-16) using partial fractions yields

$$f(S) = \prod_{k=1}^{nx5} e_k \left[\sum_{k=1}^{nx5} \frac{A_k}{S+e_k} \right] \tag{9-17}$$

where A_k is a constant to be determined.

4. Find the inverse Laplace of equation (9-17) and substituting Z for t yields for f(Z).

$$f(Z) = \prod_{k=1}^{nx5} e_k \left[\sum_{k=1}^{nx5} A_k e^{-e_k Z} \right] \tag{9-18}$$

Equation (9-18) is the required result for Z requiring only the evaluation of the constant A_k. The evaluation of these constants requires either the solution of an (nx5) x (nx5) set of equations or an (nx5) x (nx4) solution to Heavisides expansion equation. To avoid this tedious task, it was noted that each term on the right hand side of equation (9-18) was exponentially distributed and it has been shown by Tocker[9] that for even degrees of freedom

$$X^2_{2p} = \sum_{i=1}^{p} X_i \qquad (9\text{-}19)$$

where X^2_{2p} is a chi-squared variable with 2p degrees of freedom.

Equation (9-18) can be forced into the form required in equation (9-19) where $p = nx5$ and $2p = 2(nx5)$ and regardless of the value for n, X^2_{2p} always has an even number degrees of freedom. And if $2p \geq 30$, it will be sufficient to use a normal distribution as an approximation to the Chi-squared distribution. For n=6 (corresponds to six hurricanes/season) which includes 99.5% for the distribution for Y yields a Chi-squared distribution for Z with 60 degrees of freedom which is sufficient for a good normal approximation. It will therefore be assumed that Z is a normally distributed variable with mean μ_Z and variance σ_Z^2.

where $\mu_Z = E(Z)$

and $\sigma_Z^2 = E(Z^2) - \mu_Z^2$.

From equation (9-14)

$$E(Z) = \sum_{j=1}^{n} \left[\sum_{i=1}^{5} p(j) a_i m_i \right]$$

$$= \sum_{j=1}^{n} p(j) \sum_{i=1}^{5} a_i m_i$$

substituting μ_{X_i} for m_i yields

$$E(Z) = \sum_{j=1}^{n} p(j) \sum_{i=1}^{5} a_i \mu_{X_i}$$

where $p(j) = \sum_{Y=j}^{n} \frac{e^{-\lambda}(\lambda)^Y}{Y!}$

and allowing $n \to \infty$ yields as a final result

$$\mu_Z = E(Z) = \lambda \sum_{i=1}^{5} a_i \mu_{X_i} \qquad (9\text{-}20)$$

where $\sum_{j=1}^{\infty} p(j) = \lambda$

Since each term in equation (9-14) is distributed exponentially and are all mutually independent we can write

$$\sigma_Z^2 = \sum_{j=1}^{n} \sum_{i=1}^{5} (p(j) a_i m_i)^2$$

or

$$\sigma_Z^2 = \sum_{j=1}^{n} p(j))^2 \sum_{i=1}^{5} a_i^2 \mu_{X_i}^2$$

Again allowing $n \to \infty$ yields (for $p(j) = \sum_{Y=j} \frac{e^{-\lambda}(\lambda)^Y}{Y!}$

$$\sigma_Z^2 = 2\lambda \sum_{i=1}^{5} a_i^2 \mu_{X_i}^2 \qquad (9\text{-}21)$$

where

$$\sum_{j=1}^{\infty} (p(j))^2 = 2\lambda .$$

The final results for Z are

$$f(Z) = N\left(\lambda\sum_{i=1}^{5} a_i\,\mu_{X_i},\ 2\lambda\sum_{i=1}^{5} a_i^2\,\mu_{X_i}^2\right) \qquad (9\text{-}22)$$

9.5 Theoretical Derivation for α

The value for α will be found empirically from the actual historical damage data for a selected sample of hurricanes. Suppose we have a sample of size n from X (sample will come from all zones and northern U.S.) denoted X_n consisting of $(X_1, X_2, \ldots, X_n)$. And associated with this sample we have

$$A_n = (A_1, A_2, \ldots, A_n)$$
$$R_n = (R_1, R_2, \ldots, R_n)$$

where A_1R_1 is associated with X_1 for hurricane 1; A_2R_2 with X_2 for hurricane 2; . . . . . . A_nR_n with X_n for hurricane n. Then the following set of equations can be written:

$$X_1 = A_1R_1^{\alpha_1}$$
$$X_2 = A_2R_2^{\alpha_2}$$
$$\vdots$$
$$X_n = A_nR_n^{\alpha_n}$$

From this set of equations, we want an estimate of α_i (i=1,2,....,n), denoted α , such that the quantity (E^2) where*

$$E^2 = \sum_{i=1}^{n} (A_i R_i^{\alpha_i} - A_i R_i^{\alpha})^2 \tag{9-23}$$

is a minimum. Equation (9-23) can be written as

$$E^2 = \sum_{i=1}^{n} (X_i - A_i R_i^{\alpha})^2 \tag{9-24}$$

and it is this equation which must be minimized and solved for α .

Since X_i and A_iR_i are continuous, monotone functions we can minimize

$$E^2 = \sum_{i=1}^{n} \left[\log X_i - \alpha \log (A_i R_i)\right]^2 \tag{9-25}$$

and obtain the same results for α with much less effort.

Expanding equation (9-25) taking the partial derivative with respect to α , and setting this derivative equal to zero yields

$$\frac{\partial(E^2)}{\partial\alpha} = 2 \sum_{i=1}^{n} \left[(\log X_i \quad \log A_i - \alpha \log R_i)(-\log R_i)\right] = 0$$

or

$$2 \sum_{n=1}^{n} (-\log X_i \log R_i + \log A_i \log R_i + \alpha(\log R_i)^2) = 0 \tag{9-25a}$$

expanding, (9-25a) and solving for α yields

$$\alpha = \frac{\sum_{i=1}^{n} \log X_i \log R_i - \sum_{i=1}^{n} \log A_i \log R_i}{\sum_{i=1}^{n} (\log R_i)^2} \tag{9-26}$$

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* The subscript i is not the zonal notation, this i is the ith sample value out of a sample of size n. This notation as is will be used throughout section 9.3.

The expression given in equation (9-26) will be used to find α in the damage model.

As stated earlier, α is derived from a sample of past hurricane damage data and from this data three variables must be found, namely, A_i, X_i, and R_i^{α}. For a given hurricane the data for R_i^{α} and X_i is reasonably accurate but, due to inadequate records, the data for A_i is subject to a certain amount of error. It was estimated that A_i could vary up to 20% in either direction of the assumed value for any given hurricane. It will be assumed that the true value for A_i has an equally probable chance of lying anywhere in the interval $[.8A_i,\ 1.2A_i]$ for a given hurricane. Due to this uncertainty in the true value of A_i, three values of α will be calculated, namely α_L, α_M, α_H where α_L is the lower limit of α, α_M is the mean value of derived from A_i, and α_H is the upper limit of α. The range of α, namely $[\alpha_L,\ \alpha_H]$, will include 95% of the values for α obtained from the interval $[.8A_i,\ 1.2A_i]$.

To find the range of α, which includes 95% of the values for α, a n-fold change of variable problem, employing equation (9-26) must be solved where A_i is uniformly distributed variable within range $[.8A_i,\ 1.2A_i]$. Since an analytical solution to this problem is not practical; the problem will be simulated to find the distribution for α. For the simulation it is required that we be 95% confident that the sample distribution contains 99% of the values for α which will insure that the range of α contains 95% of the values for α. Using

Wilkes[3] distribution free sample size formula requires a sample of 473 to ensure the above confidence in the range. The simulation will be performed in accordance with the (α-Range) flowchart shown in the appendix.

It should be noted before leaving this section that the evaluation of R_i^α in the model must be performed in the same manner as prescribed for the evaluation of α in equation (9-26). It the average R_i^α was used in evaluating α then the average R_i^α must be used in the model for X_i. If the R_i^α cross-section density (see section (VI) for a discussion of the cross-section technique as applied to SMSA's) was used in evaluating α then the cross-section density must be employed in the model. The evaluation of R_i^α is dependent on the application and will therefore be discussed in the model application section (section (X)).

X. DAMAGE MODEL (Test Using Actual Product Data)

10.1 General

In this section, the damage model as presented in section (IX) will be tested in an attempt to determine its validity as a predictor of hurricane damage. The hurricane damage distribution for zone 6 and one other typical zone will be derived in detail and the damage distributions for all is summarized in Table XI and Table XII. There are two items of general interest which apply to all zones and will be discussed at this point, namely, (1) the product characteristics and density and (2) the determination of α (hardness factor) for the damage model.

10.1.1 Product Characteristics

It is a well known fact that the segment of industry hardest hit by hurricanes are utilities which have large segments of their investment in outside plant equipment. The product class used in this study is that of the Bell Telephone system in the area under consideration. It should be immediately pointed out that the results of this study can apply equally well to the electric utilities and any other telephone company. Since the number of items in a telephone plant which are subject to damage is very large, an indicator of damage will be used. This indicator is "number of stations affected" where a station is a subscriber's telephone set. A station, once defined, can be exploded into the product list required to support the station. Therefore, if the number of stations are known, then a very large portion of the product is defined. Furthermore, if the number of stations which are affected by a hurricane is known, then, by explosion, a large portion of the total telephone plant affected is also known. Actual data on "number of stations affected" was gathered for 17 hurricanes and is presented in the appendix in Table XVII. Unfortunately, this data covers only the time period from 1954 to the present; but this has been the problem with all hurricane data. The product density R_i in the model is then the number of stations (telephone sets) per square mile. The telephone density for any zone is a function of the population density (denoted P_i) and the proportion of Bell System telephones per person (denoted γ_i) where γ_i = (Bell System telephones in zone i)/ Total population (zone i). The telephone density for zone i is found as follows: For zone i, the land mass area was broken into counties and the population density per county was obtained from the 1960 Bureau of Census population density maps. The population density was broken down into seven classes, as shown in Table X.

TABLE X

Population Density Class Intervals

Class No.	P_i Population Density/Mi^2	Mid Class Value of P_i	R_i
1	0 - 5.0	2.5	2.5 γ_i
2	5 - 9.9	7.5	7.5 γ_i
3	10 - 24.9	17.5	17.5 γ_i
4	25 - 49.9	37.5	37.5 γ_i
5	50 - 99.9	75.0	75.0 γ_i
6	100 - 249.9	175.0	175.0 γ_i
7	250 - 750.0	500.0	500.0 γ_i

The value of P_i was then multiplied by γ_i to obtain R_i, the telephone density per square mile for zone i as shown in Table (X) and the data for R_i is shown in Table XVIII. The proportion of the total land mass area, within a zone, subject to hurricane damage* within each telephone density class was then found. This proportion was then used as an estimate of the probability that R_i takes on a given value for that zone. For example, if in zone 6 the proportion of land mass area which has a telephone density of k telephones/square mile is θ (where $0 \leq \theta \leq 1$) then the probability that $R_6 = k$ is θ. Following this procedure for each telephone density class yields a probability density function for R_i^{α} which can be used as a source of samples for R_i^{α} for the damage model. Since R_i^{α} is continuous but sampled at only seven levels, a straight line approximation will be used to estimate the value of R_i^{α} within the sampling intervals. Tables of R_i^{α} density functions are shown in the appendix in Table XVIII.

10.1.2 <u>Determination of α</u>

From section (IX), equation (9-26), it was shown that

$$\alpha = \frac{\sum_{i=1}^{n} \log X_i \log R_i - \sum_{i=1}^{n} \log A_i \log R_i}{\sum_{i=1}^{n} (\log R_i)^2} \qquad (10\text{-}1)$$

For a sample for X, it was decided to study the hurricanes from 1954

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* Land mass area subject to hurricane damage - that land mass area within a zone between the coastline and the maximum hurricane penetration line.

through 1961 to find the data required in equation (10-1). This time period included 12 hurricanes each of which was studied in some detail from the writeups contained in the Monthly Weather Review which yielded the results shown in Table XIX. Out of the twelve hurricanes, only nine yielded results which could be used in equation (10-1). From the nine hurricanes it was found that α_m, the mean value of α was equal to .575. Performing the α-range simulation outlined in Section (9.5), with the specified sample size, it was found that α was normally distributed with mean μ_α and variance σ_α^2 where

$$\mu_\alpha = .576$$

$$\sigma_\alpha^2 = .0001285.$$

The range of α was then found by equation (10-2).

$$\text{Prob } (\alpha_L \leq \alpha \leq \alpha_H) = .95. \qquad (10\text{-}2)$$

where α is normally distributed. From this equation it was found that $\alpha_L = .554$ and $\alpha_H = .598$. It is this range of α which will be used hereafter in this study.

10.2 Damage Model Application

10.2.1 General

Once again, the damage models for the zones are

$$X_i = D_i R_i^\alpha \left(S_i T_i + \frac{D_i}{2}\right) \qquad \text{for zones } 1,2,3,4,5$$

and

$$X_6 = 140\ D_6 R_6^\alpha \qquad \text{for zone } 6.$$

The input data for the above models is given in Table IX, section 8.4

for D_i, S_i and T_i and the input data for R_i^{α} (for three levels of α) is given in Table XVIII. Due to the small geographical area included in zone 5 it was decided to group zone 5 and zone 4 together and denote this larger zone as zone 4 (or zone 4,5). To find the mean and variance for the zonal damage distributions it was necessary to find $E(D_i^3)$ and $E(D_i^4)$ and these values are given with the diameter data in the appendix. All mean, variance, simulations, α, R_i^{α}, etc. calculations were performed on the IBM 1620 computer requiring the use of 22 programs, none of which shall be included in this paper.

10.2.2 Damage Distribution (zone i)

As argued in Section (9.3), the determination of the damage analytically was not feasible due to the complexity of the damage model and input distributions. For this reason it was decided to run a simulation to determine the shape of the damage distribution. Even though the distribution could not be determined analytically, the mean and variance can be calculated using equations (9-5) and (9-6) and these values are shown in Table XX for all zones.

The damage distribution simulation was run for two cases, the first being for zone 6 and second being for zones one through zone five. The simulation for zone 6 converged within 10% of the mean and variance with a sample size of 175 yielding a negative exponential distribution at the 95% confidence level. It was then assumed that X_6 was distributed according to a negative exponential distribution with mean μ_{X_6} as shown in Table XI. Since the input variables for the other zones were all distributed in the same manner, differing only in the mean and variance, it was decided to simulate using typical distributions with the assumption being that the results would be the same as if the actual distributions were used. In this case the simulation converged within 10% of the mean and variance with a sample size of 200 yielding a negative exponential distribution at the 95% confidence level. This simulation was repeated three times and was found to be consistent. All simulations were run using the three levels of α and it was found that α did not affect the results for the range indicated in section (10.1.2). The summarized results for the zonal damage is shown in Table XI at the end of this section for the range of α.

The results shown in Table XI is the damage distribution given that a hurricane passes through a zone. The damage distribution for each zone for one hurricane season denoted $\bar{X}_i$ is then

$$\bar{X}_i = \lambda a_i X_i \tag{10-3}$$

as derived in Section (9.4) where

$$X_i = \frac{1}{\mu_{X_i}} e^{-X_i/\mu_{X_i}}$$

and by a change of variable

$$\bar{X}_i = \frac{1}{\lambda a_i \mu_{X_i}} e^{-\bar{X}_i/\lambda a_i \mu_{X_i}} \tag{10-4}$$

and

$$\mu_{\bar{X}_i} = \lambda a_i \mu_{X_i} \tag{10-5}$$

From Section 6.1 equation 6-1

$$\lambda = 1.97$$

and from Section 6.2 Table III , Section 6-3 Table V and Section 9.4 (Equation 9.9a).

$$a_1 = .138$$

$$a_2 = .123$$

$$a_3 = .188$$

$$a_4 = .551 \quad \text{(zones 4 and 5)}$$

$$a_5 = .245 \quad \text{(zone 6)}$$

and the values for μ_{X_i} are given in Table XI.

Substituting the above values into equation 10-4 and 10-5 yields the distributions for $\overline{X}_i$ (at three α levels) as shown in Table XI. Also included in Table XII is the 90% confidence range for the value of $\overline{X}_i$ denoted $[\overline{X}_i^L , \overline{X}_i^U]$ where

$$\overline{X}_i^L = \text{Prob } (\overline{X}_i \leq \overline{X}_i^L) = .025 \text{ for } \alpha_L$$

and

$$\overline{X}_i^U = \text{Prob } (\overline{X}_i \geq \overline{X}_i^U) = .975 \text{ for } \alpha_H.$$

Even though this range includes 95% of the values for $\overline{X}_i$, it is only a 90% range since we are only confident that 95% of the values for α are included in the distribution and (95%)(95%) = 90%. The damage distribution can also be found on a monthly basis by employing the arguments set forth in Section (IX) and the probabilities in Section (VI) although it will not be done in this paper.

10.2.3 Damage Distribution (Southern U.S.)

As shown in Section 9.4, the damage Z for the entire area under study is normally distributed with mean μ_Z and variance σ_Z^2 where

$$\mu_Z = \lambda \sum_{i=1}^{5} a_i \mu_{X_i} \tag{10-6}$$

$$\sigma_Z^2 = 2\lambda \sum_{i=1}^{5} a_i \mu_{X_i}^2 \tag{10-7}$$

The values for λ, a_i, and X_i are presented in Section (10.2.2) and Table XI. Substituting these values into equations (10-6) and (10-7) yield the distributions for Z (at three α levels) as shown in Table XII. Also included in Table XII is the 90% confidence range for Z where the range is calculated as shown in Section (10.2.2).

10.3 Discussion and Verification of Results

As shown in Table XII, the results for zonal damage ($\bar{X}_i$) and the results for the entire Southern United States (Z) are given for three different levels of α. Also shown in the same Table is the 90% confidence interval on the results. It can be readily seen that each value of α in the interval $[\alpha_L, \alpha_H]$ will yield a different distribution of damage. While these distributions do not change in shape (Z is normally distributed for any value of α in the interval) they do differ in both the mean and the variance.

To verify the results for Z obtained in Table XII, for the product and product densities used, one must determine if the distribution of a sample of actual damage data points falls within the 90% confidence interval for Z for the given α interval. Reference to Table XVII in the appendix will yield a sample of hurricane damages for the Southern United States. It will be immediately noted that some of the damage figures in this sample were used to find the value and range of α. Is it legal to use them again? Strictly speaking, I think the answer would have to be no; but they will be used and for the following reasons:

1. This is all the data available.
2. It was found that the mean squared error defined by equation (9-23) did not change significantly when the Southern hurricanes were excluded from the sample used to determine α. This implies that the value of α used in the model is not dependent to any extent on the Southern hurricanes.

Using the sample in Table XVIII, we find one disturbing damage figure, namely, Hurricane Betsy, with 529,000 stations affected. This value is an outlier to both the distribution obtained for Z and the sample distribution of damage. One unusual characteristic of Betsy was that it was accompanied by an abnormal amount of flooding in the New Orleans SMSA. Flooding of this magnitude will increase the total number of stations affected to a very high figure. For this reason, the Hurricane Betsy damage figure will not be included in the sample. However, if more figures of this magnitude occur in the future, a re-evaluation of the model presented in this paper will be required.

It was found that the sample values were normally distributed (at 95% level) with a mean of 78,700 stations/year and a standard deviation of 53,400 stations affected/year. Comparing these distribution parameters with the distribution for Z (at α_M) in Table XII it was found that there existed no statistical difference between the variances (by F-test at the 95% level with samples of 10,10) and no difference between the means (by t-test at the 95% level with samples of 10,10). It can therefore be concluded that the model met its objective based on the sample for aotual damage data for the years 1955 through 1964. Based on the distribution of this sample, with the mean and variance given above, and the distribution for Z (at α_M) it was concluded that the model would predict within the 90% confidence interval for Z (at α_M) approximately 86% of the time. It can therefore be concluded that the model will perform as a good predictor to determine the number of stations affected, in the Southern U.S., in the future providing there exists no change in the input variables, alpha, the product, or the product density.

The zonal damage based on the sample from Table XVII is shown in Table XXI below.

Table XXI
Actual Zonal Damage, 1955-65*, Est.
Number of Stations Affected

Damage	Zone	Damage/year	No. of Hurricanes
166,000	1	16,600	1
83,000	2	8,300	1
164,000	3	16,400	3
89,500	4	8,950	5
	5		
294,000	6	29,400	4

*Hurricane Betsy Excluded.

Comparing the damage/year in the above table with the expected damage distributions in Table XII reveals that all the values lie within the 90% confidence interval of their respective zonal expected damage distributions. It is felt that due to the small sample of hurricanes in each zone a statistical test cannot be made with any confidence.

Table XI

Hurricane Damage Summary (X_i)

(Telephone Stations Affected)

	X_i Stations Affected Zone i α_L	X_i Stations Affected Zone i α_M	X_i Stations Affected Zone i α_H
ZONE ONE	Exponential* m_1=19675	Exp. m_1=21307	Exp. m_1=23103
ZONE TWO	Exp. m_2=38021	Exp. m_2=41317	Exp. m_2=44918
ZONE THREE	Exp. m_3=28674	Exp. m_3=30628	Exp. m_3=32791
ZONES FOUR AND FIVE	Exp. m_4=22145	Exp. m_4=23826	Exp. m_4=25675
ZONE SIX	Exp.. m_6=46609	Exp. m_6=50588	Exp. m_6=54972

* $f(X_i) = \frac{1}{\bar{m}_i} e^{-(X_i/m_i)}$, where $m_i = \mu_{X_i}$

Table XII

Hurricane Damage Summary ($\bar{X}_i$, Z)

(Telephone Stations Affected)

	α_L	α_M	α_H	90% Confidence Interval LOWER BOUND	90% Confidence Interval UPPER BOUND
$\bar{X}_1$ Zone 1	Exponential* $\bar{m}$=5349	Exp. $\bar{m}$=5792	Exp. $\bar{m}$=6280	134	19800
$\bar{X}_2$ Zone 2	Exp. $\bar{m}$=9214	Exp. $\bar{m}$=10012	Exp. $\bar{m}$=10884	230	34000
$\bar{X}_3$ Zone 3	Exp. $\bar{m}$=10620	Exp. $\bar{m}$=11343	Exp. $\bar{m}$=12145	266	39200
$\bar{X}_4$ Zones 4&5	Exp. $\bar{m}$=24038	Exp. $\bar{m}$=25862	Exp. $\bar{m}$=27870	600	88500
$\bar{X}_5$ Zone 6	Exp. $\bar{m}$=22495	Exp. $\bar{m}$=24416	Exp. $\bar{m}$=26532	563	83000
Z	Normal Mean=71716 STD=36462	Normal Mean=77425 STD=39371	Normal Mean=83711 STD=42572	216	167211

* $\bar{X}_i = \frac{1}{\bar{m}} e^{-(\bar{X}_i/\bar{m}_i)}$, where $\bar{m}_i = a_i \mu_{X_I}$

XI CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

The major objective of this paper is to present a model for predicting, within a confidence interval, physical hurricane damage for a hurricane season in the Southern United States. This model, as developed, is presented in sections 9.2 and 9.4. The inputs to the model are data concerning the areal coverage of a hurricane and the product for which an estimate of the damage is desired. The output of the model is a probability density function for the level of expected damage/year and from this density function a confidence interval can be placed on the results.

A test was performed on the model using actual product data in an attempt to evaluate the model as a predictor of hurricane damage. The product data was the "number of Bell System telephone stations affected" for hurricanes in the years 1955 through 1964. The test was performed with 10 years of actual data at two levels, namely (1) to predict the damage/year for this product for the entire Southern United States and (2) to predict the damage/year in six zones within the Southern United States area. These results are shown in Tables XII and discussed in section (10.3). It was found, based on this sample of actual data, that for the entire southern area the model will yield a prediction within the 90% confidence interval of the actual damage approximately 86% of the time per year given stationary input variables. The test for the zones was not conclusive due to the small sample of actual data within each zone, however, it was found that all the actual mean zonal damage/year values lay within the confidence interval placed on the zonal predicting distributions shown in Table XII.

From this test and other tests performed throughout this paper the following conclusions and observations concerning the damage model can be made:

1. The damage distributions derived from this model will provide a better basis for predicting damage than an intuitive guess or a straight averaging technique. A guess or an averaging technique will not provide the decision maker with the variability of the damage or the shape of the damage distribution. This added information will change a decision based on hurricane damage to one under risk rather than uncertainty.

2. This model will allow one to find the expected damage at any location in the Southern hurricane belt. If one wishes to know the expected damage in the Miami SMSA, he can do so readily using the hurricane probabilities and variable analysis set forth in this paper. He will be required to know the product density in Miami for the product in question.

3. The model is such that it can be applied equally well in any geographical area. The model is not dependent on any physical factor which is a function of the area a hurricane will cross.

4. The model will track changes in hurricane damage characteristics. The tracking ability, of course, is a function of how the user maintains or up-dates his input data.

5. The hardness factor (α) allows one to adjust the damage distribution to fit a given area. If it is thought that the product in a certain area is less susceptable to damage then the average then

the α can be decreased to decrease the mean of the damage distribution. The sensitivity of the model to changes in α is discussed in sections (9.5) and (10.1.2). In other words, the model allows for usage of some subjective judgment on the part of the user.

6. The model is easy to use, requiring only the maintenance of two variables (A_i and R_i) which makes it readily adaptable to hand calculation or if more sophistication is sought, a relatively small computer program will handle the whole job.

7. The model will be conservative for estimating damage over large areas since it weighs the damage in SMSA's and the damage in rural regions equally thus minimizing the very large damage that can occur in a SMSA. This is due to the decision to use average product density rather than the product cross-section density. As the population dansity increases along the Southern coastline, as it will as indicated in the large increase over the last 20 years, the cross-section density will probably have to be used. For a discussion of cross-section densities, see section 6.4.

The decision to use the zones presented in this paper was out of convenience; the model will work for any other set of zones except that one will have to refer to the hurricane literature for the basic data on the hurricane variables and regroup for the new set of zones. It must be remembered that the damage distributions derived in this paper are valid only for the product used, namely the number of Bell System telephone stations affected, and they may or may not be the same for another product with a different density frequency function. However, the techniques shown are valid for any product density frequency function and these techniques must be reapplied each time there is a change in the product or product density. It is suspected, but not proven, that the damage distributions will be the same for any reasonable distribution of product density. A highly skewed distribution may give some problems in this respect. The use of α is fully discussed in Appendix II.

Recommendations for Further Study

Since this paper represents, to the author's knowledge, the first work in this area there are a multitude of areas which require study. Some of these are:

1. Apply model to another product and see if it produces reasonable and consistent results.

2. This model does not account for flooding due to storm surges along the Gulf coast. It was assumed that the effect of storm surges is minimized by levies along the coast. However, this requires further study to see if this is the case.

3. The use of cross-section product density rather than average product density should be investigated more fully.

4. A multiple regression technique applied to the hurricane variables may shed some additional information on the affect of each variable in the model. Perhaps a different class of model is required.

5. Some of modeling required simulations, perhaps more analytical work on convolution of the hurricane variables would yield more accurate results.

These are but a few of the areas in which further work is required and the reader will probably see many others.

APPENDIX I

HURRICANES REACHING U.S. COAST

(1900 - 1960)

10 Year Moving Average

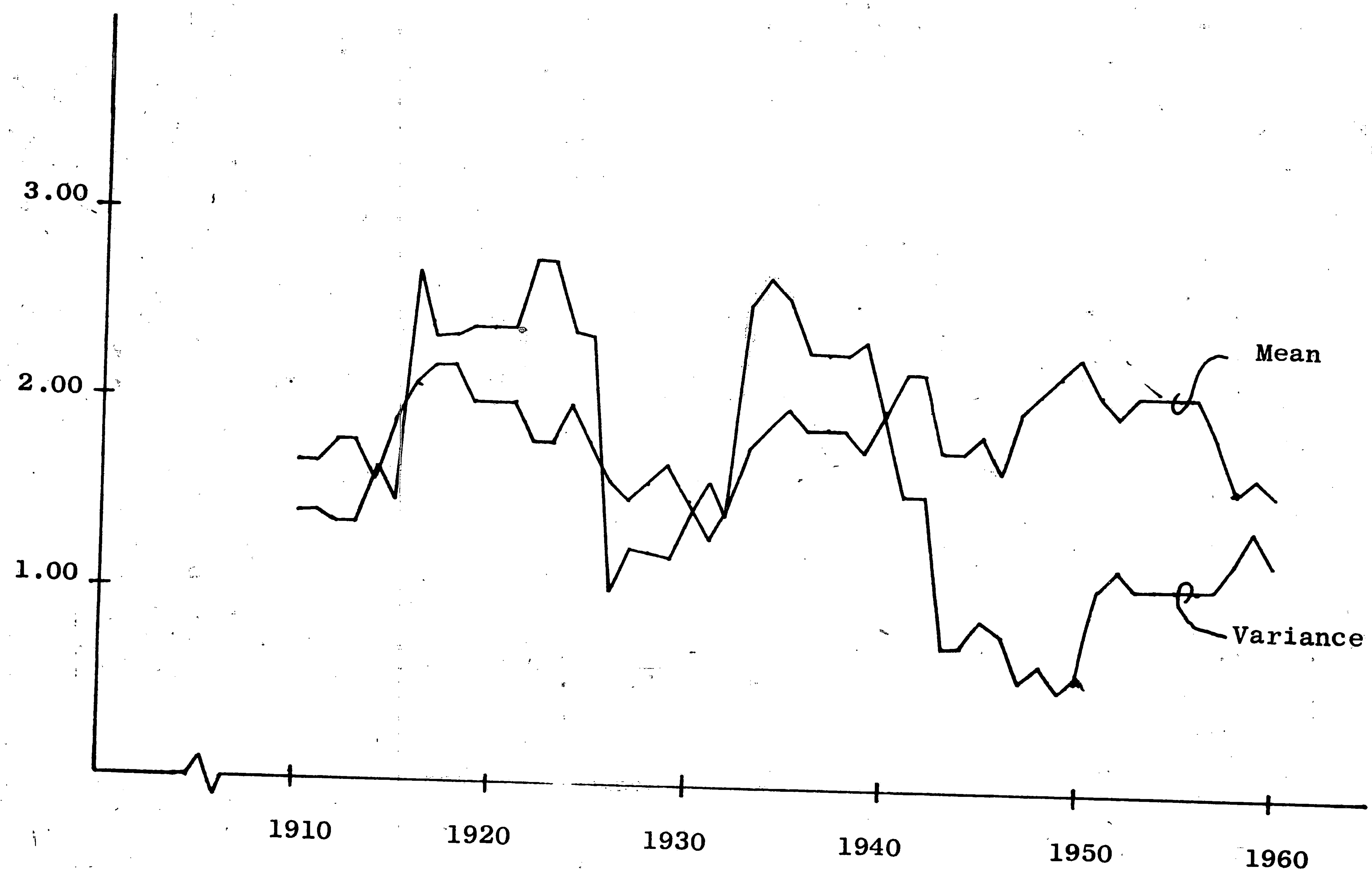

Figure 9

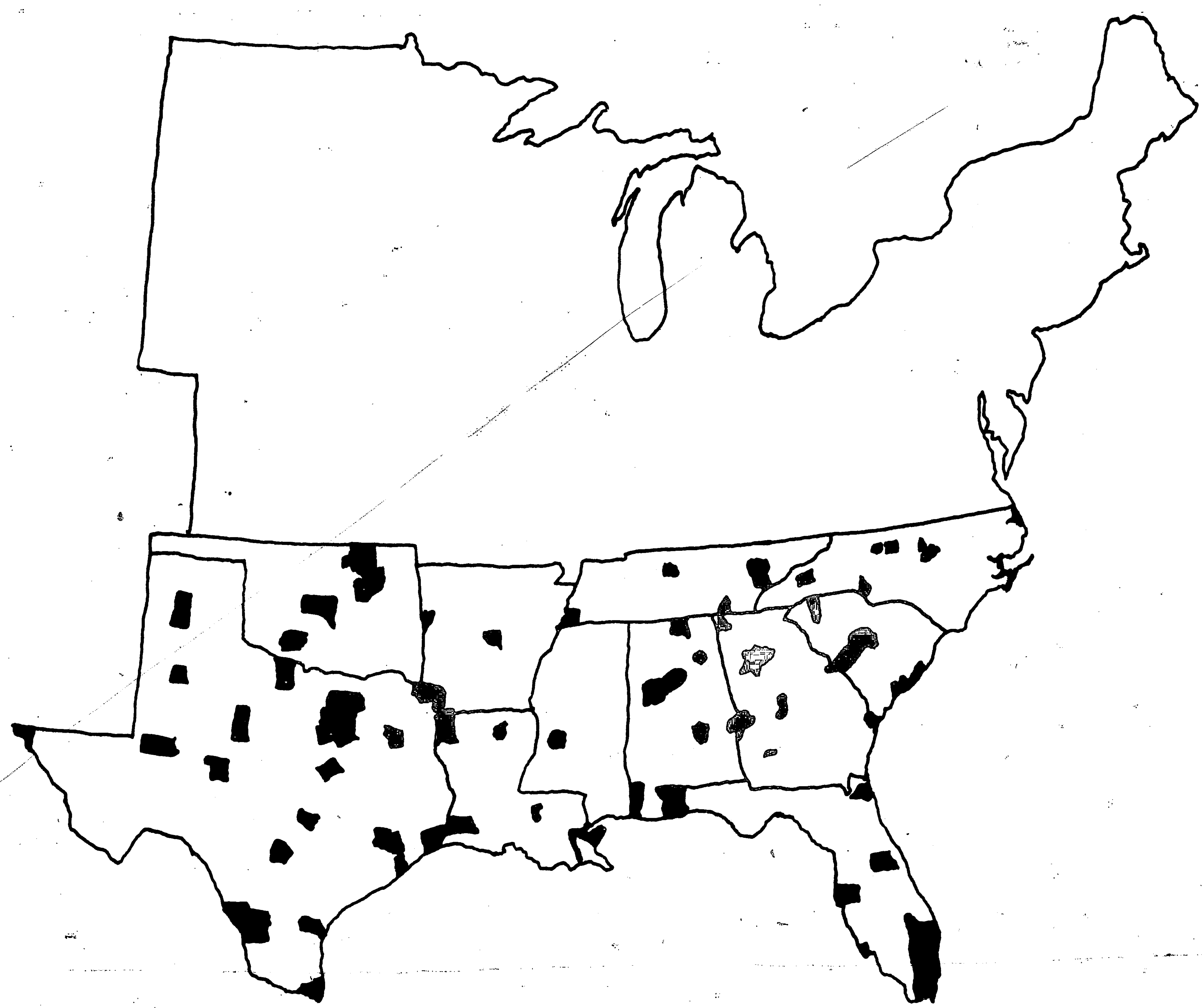

Figure 10: Standard Metropolitan Statistical Areas Southern United States 1960

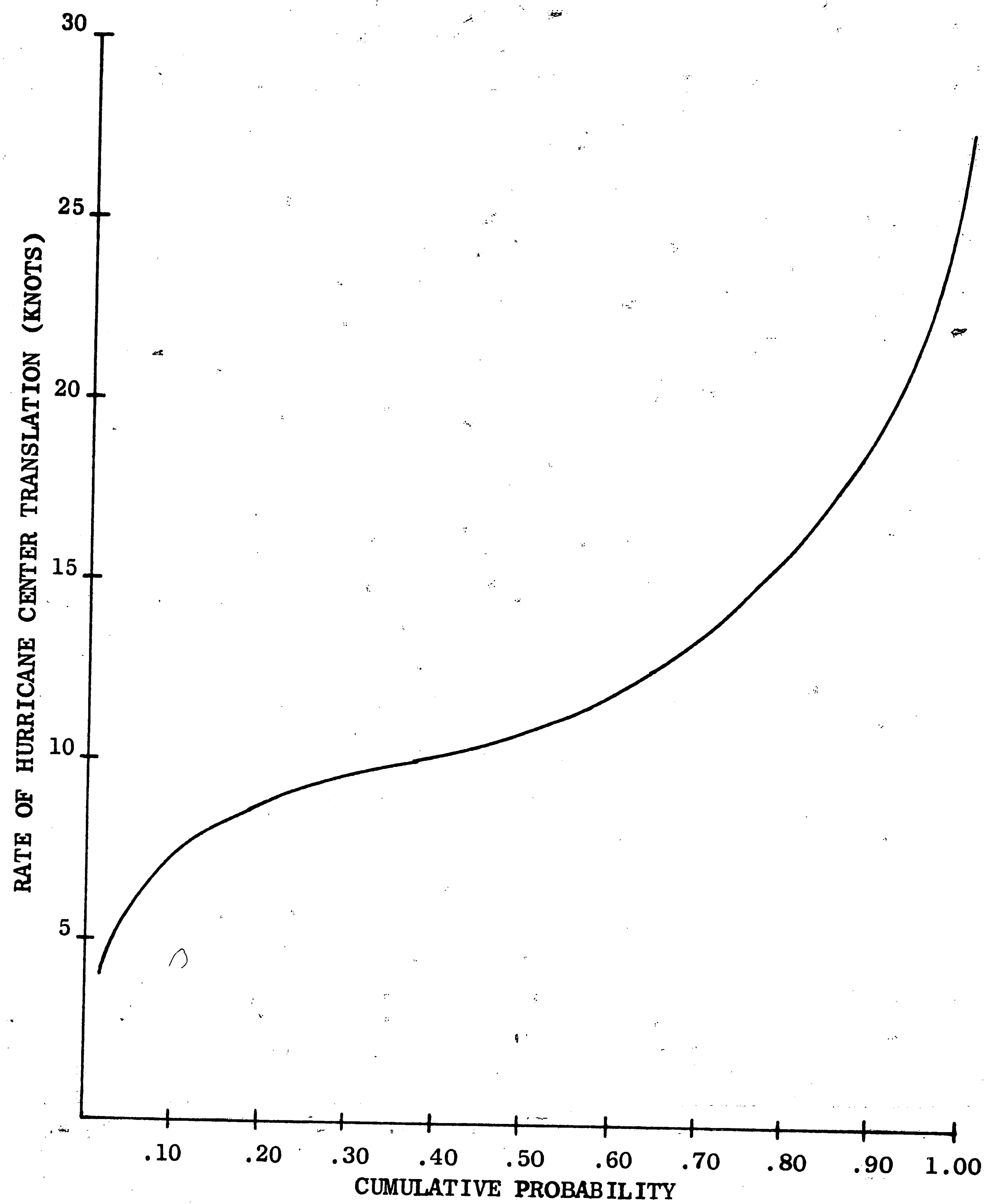

Figure 11: Cumulative Distribution of the Rate of Hurricane Center Translation. Gulf Coast (1900 - 1956)[5]

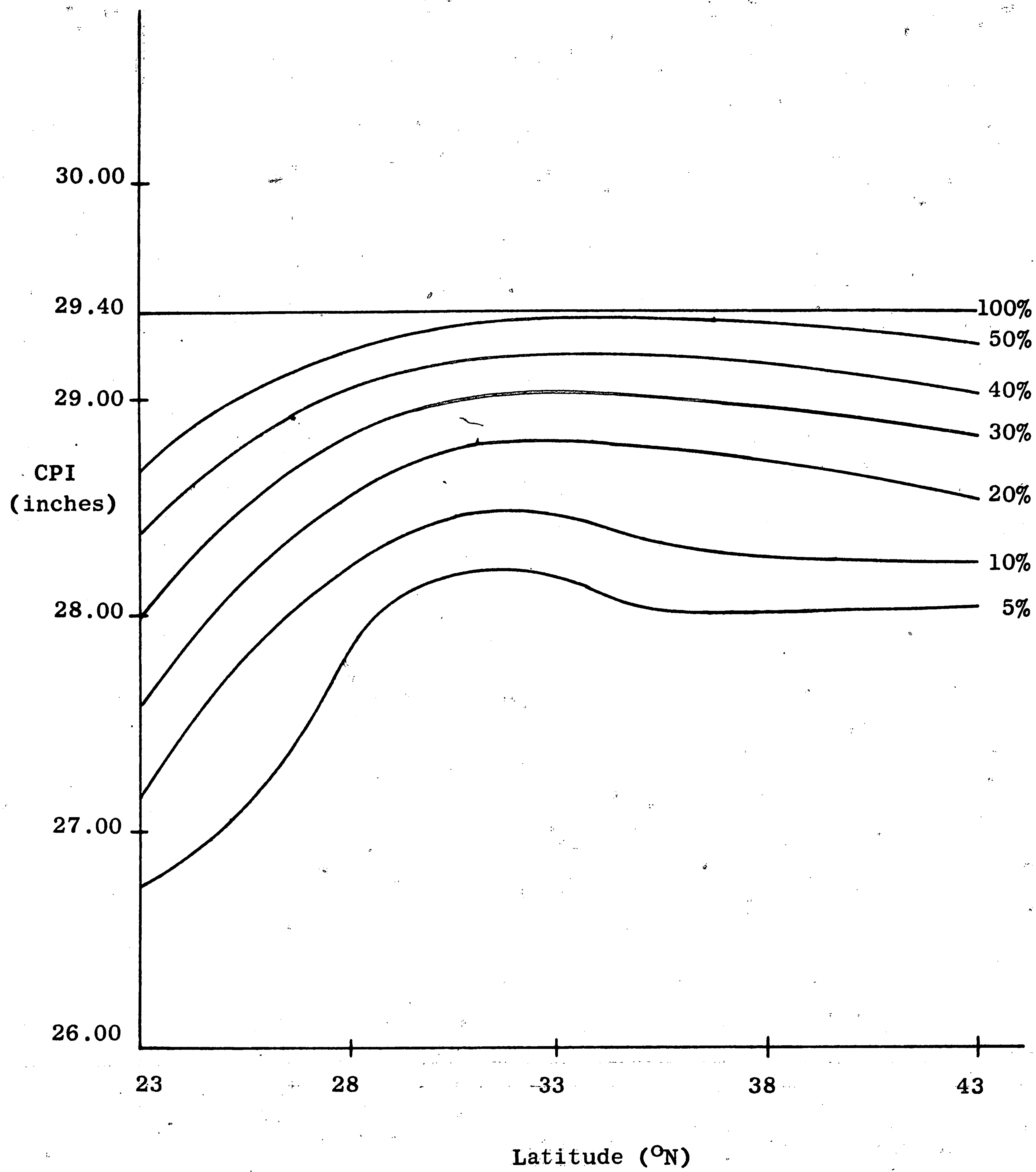

Figure 12: Latitudinal Variation of Cumulative Frequency of Hurricane Central Pressure Index East Coast (1900 - 1956)[5]

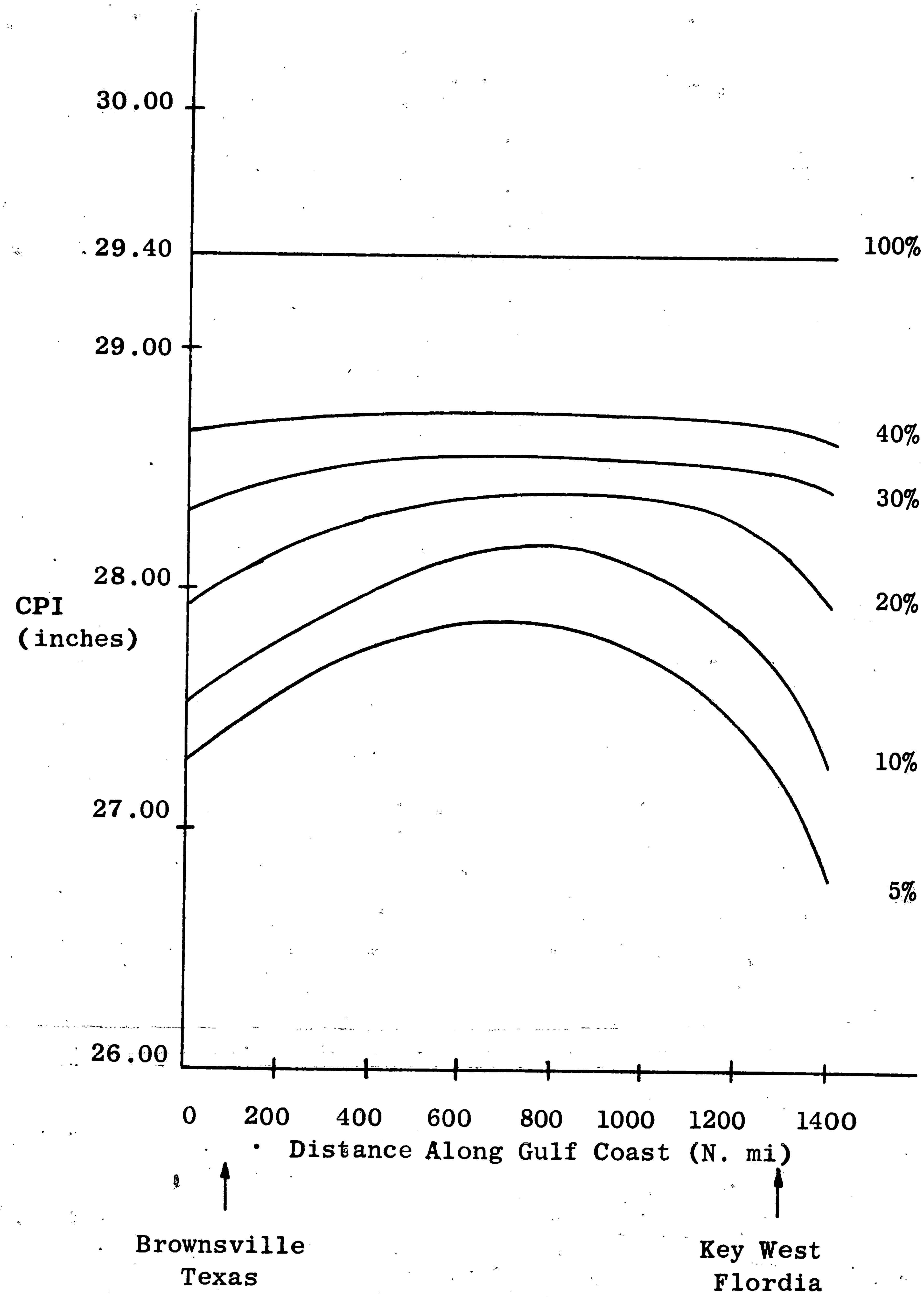

Figure 13: Geographic Variations of Cumulative Frequency of Hurricane CPI Gulf Coast (1900 - 1956) (5)

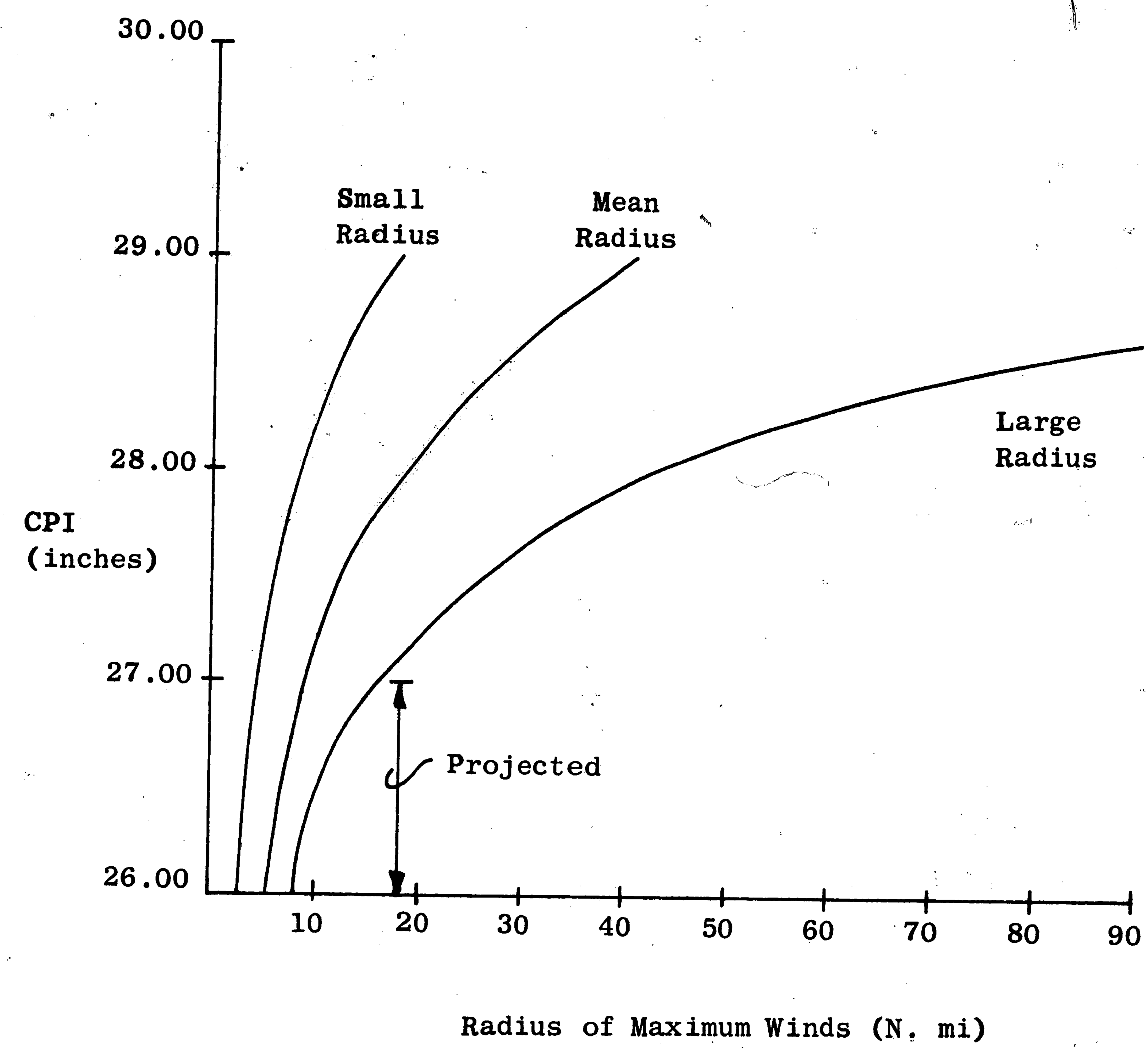

Figure 14: Envelope of the Variation of the Radius of Maximum Winds with CPI Gulf Coast (1900 - 1956) (5)

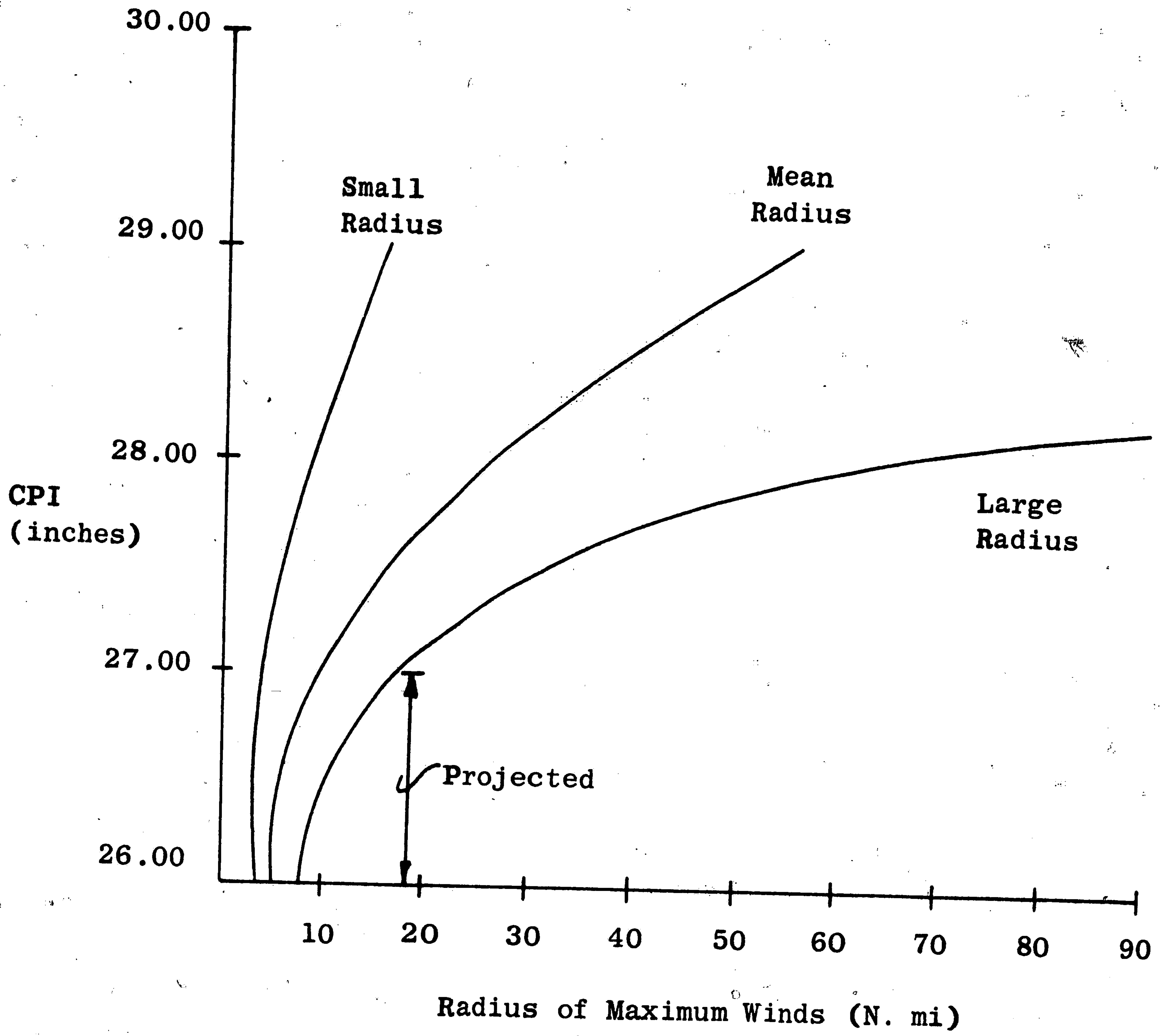

Figure 15: Envelope of the Variation of the Radius of Maximum Winds with CPI Atlantic Coast (1900 - 1956) (5)

α RANGE FLOWCHART

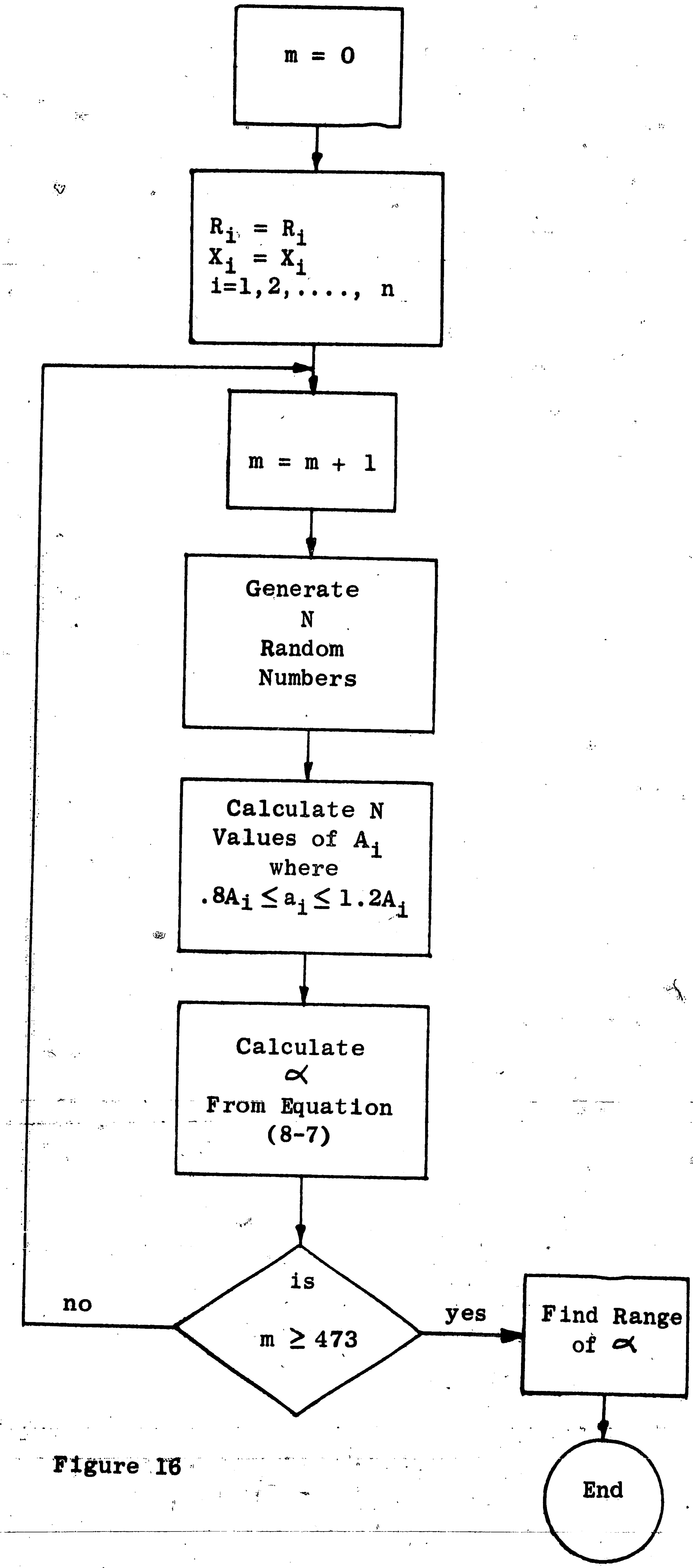

Figure 16

X_i DISTRIBUTION SIMULATION

Flowchart

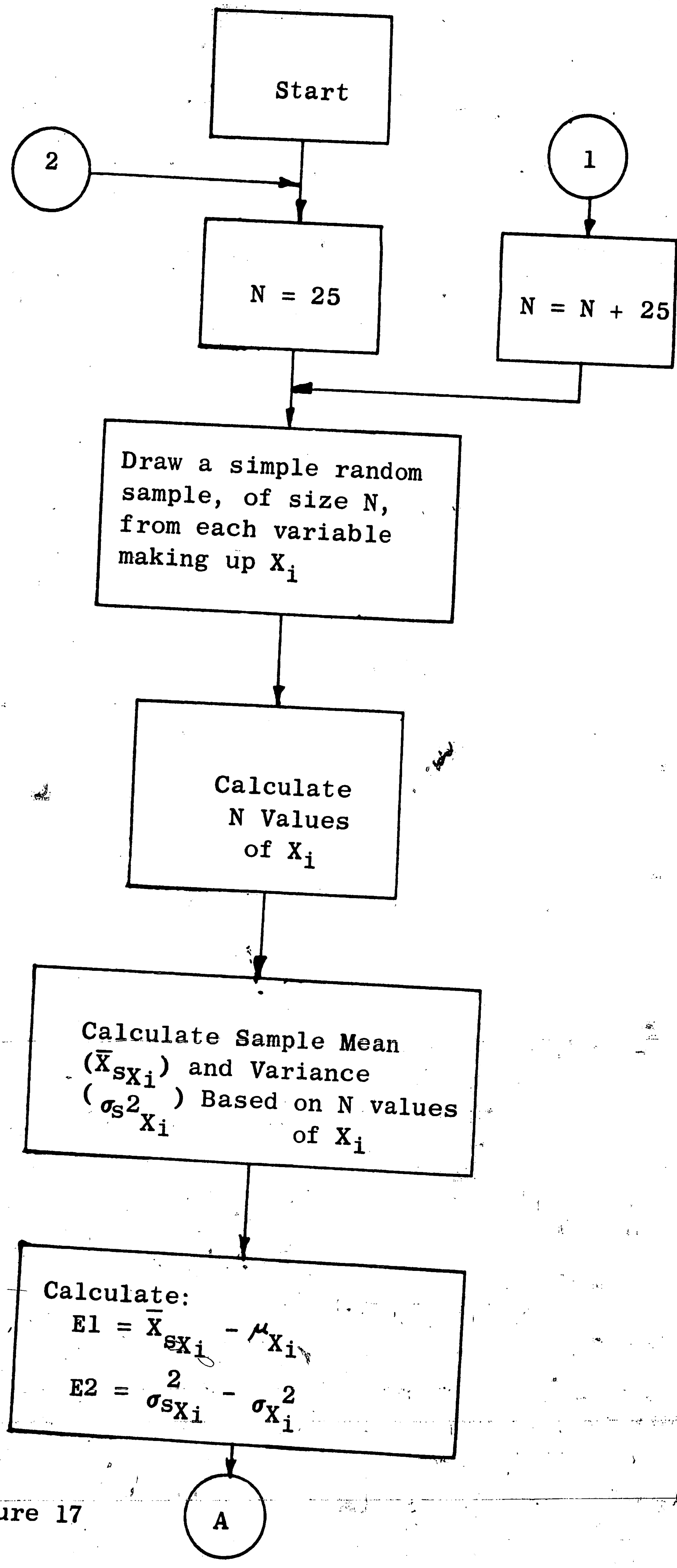

Figure 17

X_i DISTRIBUTION SIMULATION

Flow Chart (Cont.)

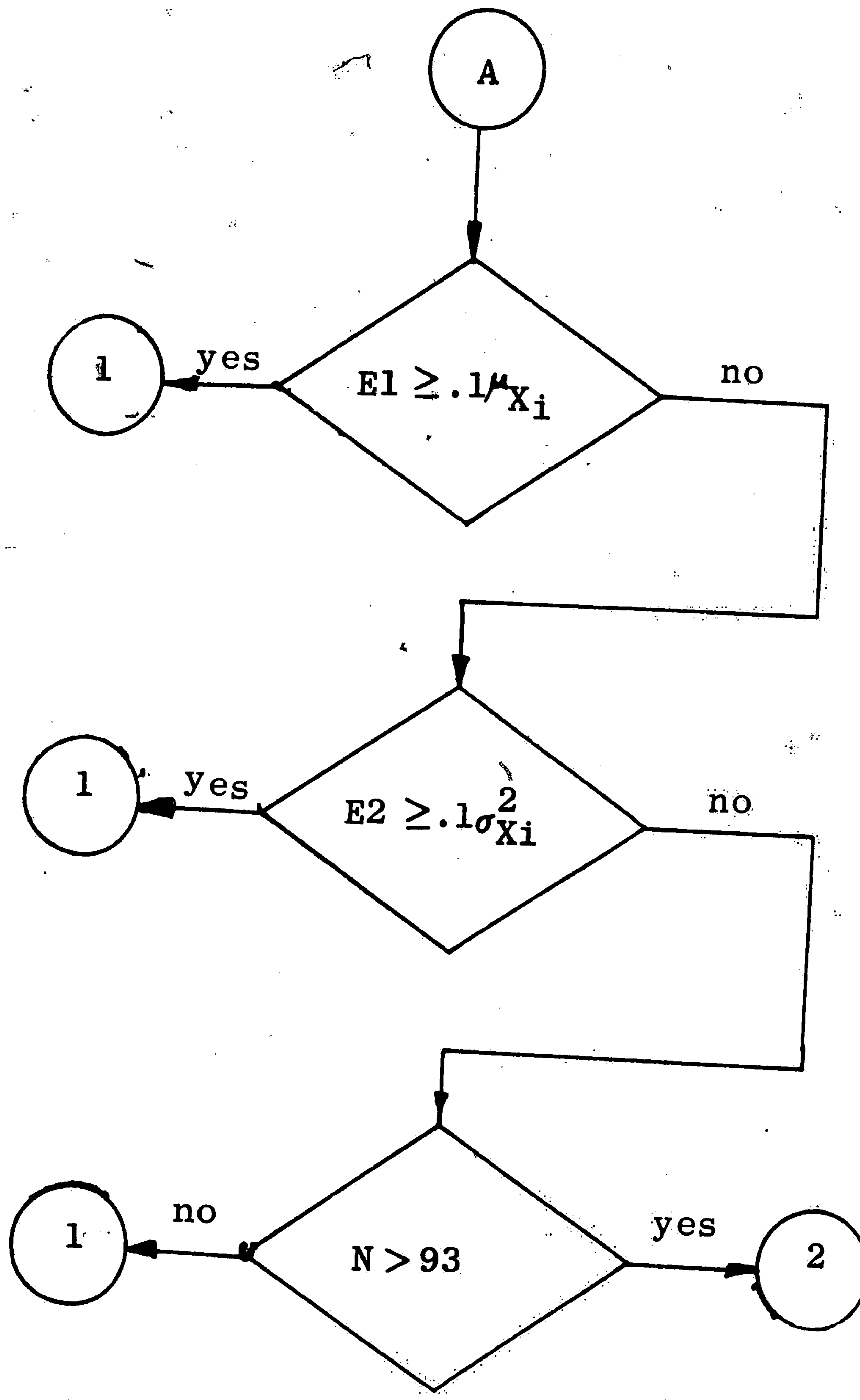

TABLE XIII

Hurricanes Reaching Coast (1887 - 1960)

Year	Number	Year	Number	Year	Number
1887	3	1914	0	1941	2
1888	3	1915	3	1942	2
1889	2	1916	6	1943	1
1890	0	1917	1	1944	3
1891	2	1918	1	1945	3
1892	0	1919	1	1946	1
1893	6	1920	2	1947	3
1894	2	1921	2	1948	3
1895	1	1922	0	1949	2
1896	4	1923	2	1950	3
1897	1	1924	1	1951	0
1898	3	1925	1	1952	1
1899	3	1926	4	1953	2
1900	1	1927	0	1954	3
1901	2	1928	2	1955	3
1902	1	1929	2	1956	1
1903	2	1930	0	1957	1
1904	2	1931	0	1958	0
1905	0	1932	2	1959	3
1906	4	1933	5	1960	2
1907	0	1934	3		
1908	1	1935	2		
1909	3	1936	3		
1910	2	1937	0		
1911	2	1938	2		
1912	2	1939	1		
1913	2	1940	2		

TABLE XIV

Hurricane Crossings By Zone and Month

(1887 - 1950)

		Month						
		June	July	August	Sept.	Oct.	Nov.	Totals
Zone	1	9	8	11	10	5	0	43
	2	3	6	8	17	4	1	38
	3	5	8	11	24	10	1	59
	4	5	7	11	30	23	2	78
	5	6	9	14	30	31	4	94
	6	9	7	15	30	35	5	102
Totals		37	45	70	142	108	12	414

TABLE XV

Speed Data (Knots)

Zone	1	2	3	Grouped 4 5	6
	6	8	7		6.5
	6	10	8	~~8~~	6.5
	6	8	8	7	6.5
	8	11	13	8	8.0
	8	17	15	11	8.0
	9	24	15	13	10.0
	10	23	15	15	10.0
	10		15	16	10.0
	10		17	22	10.0
	10		22	26	11.0
	10		22		11.0
	10.5		23		12.0
	10.5		26		13.0
	11				13.0
	13				14.0
	13				17.0
	14				
	16				
	17				

TABLE XVI

Diameter vs. CPI

Zone 1

D_1 (miles)	C_1 (inches)
32	27.64
28	27.80
41	28.04
46	28.08
81	28.00
46	28.28
41	28.78
25	28.76
37	28.76
58	28.80
64	28.86

$E(D_1^3) = 140{,}000$

$E(D_1^4) = 9{,}000{,}000$

TABLE XVI, (Cont.)

Diameter vs. CPI

Zone 2

D_2 (miles)	C_2 (inches)
67	27.88
64	28.90
64	28.90
76	28.56
60	28.30
76	28.68
25	28.80
44	28.76
150	28.80
64	28.86
32	27.64
57	28.80
81	28.00
46	28.28
28	27.80

$E(D_2^3) = 480,000$

$E(D_2^4)$ 57,600,000

TABLE XVI, (Cont.)

Diameter vs. CPI

Zone 3

D_3 (miles)	C_3 (inches)
67	27.88
39	28.20
32	28.28
60	28.30
44	28.44
25	28.80
37	28.76
44	28.76
41	28.98
48	28.96
64	28.90
76	28.48
76	28.56
76	28.68
85	28.52
115	28.38
150	28.80
168	28.50

$E(D_3^3) = 848{,}000$

$E(D_3^4) = 128{,}200{,}000$

TABLE XVI, (Cont.)

Diameter vs. CPI

Zones 4 & 5

D_4 (miles)	C_4 (inches)
29.9	28.55
32.2	28.35
62.1	28.75
62.1	28.90
80.5	28.90
103.0	28.43
115.0	28.50

$E(D_4^3) = 439{,}000$

$E(D_4^4) = 46{,}500{,}000$

TABLE XVI, (Cont.)

Diameter vs. CPI

Zone 6

D_6 (miles)	C_6 (inches)
13.8	26.35
34.5	27.45
48.3	27.50
55.2	27.60
121.9	27.60
78.2	27.73
66.7	28.00
55.2	28.10
52.9	28.13
50.6	28.30
32.2	28.33
34.5	28.40
57.5	28.80
59.8	28.90
69.0	28.81
80.5	28.80
98.9	28.80

$E(D_6^3) = 325,000$

$E(D_6^4) = 29,700,000$

TABLE XVII

Stations Affected For Hurricanes Since 1954

Hurricane	Year	Number of Stations Affected
Carol	1954	334,000
Edna	1954	294,000
Hazel	1954	449,000
Connie	1955	241,000
Diane	1955	190,000
Ione *	1955	12,000
Flossy *	1956	38,000
Audrey *	1957	83,000
Gracie *	1959	56,000
Donna	1960	490,000
Carla *	1961	166,000
Esther	1961	66,000
Cleo *	1964	149,000
Dora *	1964	98,000
Hilda *	1964	120,000
Isabell *	1964	25,000
Betsy *	1965	529,000

* Southern United States Hurricane

TABLE XVIII

Distribution of R_i^{α} for all Zones

Zone One (γ_1=.316)

Population Density P_1		α_L	α_M	α_H	Prob. of R_1^{α} for $\alpha_L \leq \alpha \leq \alpha_H$
2.5		.87	.87	.86	.19
7.5		1.61	1.64	1.67	.10
17.5		2.57	2.67	2.78	.27
37.5		3.93	4.15	4.38	.19
75.0		5.77	6.19	6.63	.06
175.0		9.23	10.08	11.01	.06
500.0		16.52	18.46	20.64	.13
$\mu_{R_1^{\alpha}}$	=	4.82	5.22	5.66	
$\sigma^2_{R_1}$	=	24.51	31.13	39.47	

Zone Two (γ_2=.344)

$$R_2^{\alpha} = (\gamma_2 P_2)^{\alpha}$$

P_2		α_L	α_M	α_H	Probability of R_2^{α}
2.5		.91	.91	.92	.03
7.5		1.69	1.72	1.76	.00
17.5		2.70	2.81	2.92	.25
37.5		4.12	4.36	4.61	.38
75.0		6.05	6.50	6.98	.09
175.0		9.68	10.59	11.59	.12
500.0		17.31	19.39	21.71	.13
$\mu_{R_2^{\alpha}}$	=	6.23	6.77	7.36	
$\sigma^2_{R_2^{\alpha}}$	=	23.05	29.62	37.99	

TABLE XVIII (Cont.)
Zone Three (γ_3=.260)

$$R_3 = (\gamma_3 P_3)$$

P_3		α_L	α_M	α_H	Probability of R_3^α
2.5		.78	.78	.77	.00
7.5		1.44	1.46	1.49	.30
17.5		2.31	2.39	2.47	.06
37.5		3.53	3.71	3.90	.33
75.0		5.18	5.53	5.90	.19
175.0		8.28	9.01	9.80	.06
500.0		14.82	16.50	18.37	.06
$\mu_{R_3^\alpha}$	=	4.11	4.39	4.70	
$\sigma^2_{R_3^\alpha}$	=	10.59	13.29	16.65	

Zone Four and Five ($\gamma_{4,5}$=.245)

$$R_4^\alpha = (\gamma_{4,5} P_{4,5})^\alpha$$

$P_{4,5}$		α_L	α_M	α_H	Probability of R_4^α
2.5		.76	.75	.74	.02
7.5		1.40	1.41	1.43	.02
17.5		2.23	2.31	2.38	.11
37.5		3.41	3.58	3.76	.44
75.0		5.01	5.34	5.70	.17
175.0		8.02	8.71	9.46	.13
500.0		14.34	15.95	17.72	.11
$\mu_{R_4^\alpha}$	=	5.27	5.67	6.11	
$\sigma^2_{R_4^\alpha}$	=	13.29	16.84	21.29	

TABLE XVIII (Cont.)
Zone Six (γ_6=.284)

P_1		α_L	α_M	α_H	Probability of R_6^α
2.5		.82	.82	.81	.12
7.5		1.52	1.54	1.57	.16
17.5		2.43	2.51	2.60	.08
37.5		3.70	3.90	4.11	.16
75.0		5.44	5.82	6.22	.12
175.0		8.70	9.48	10.33	.24
500.0		15.57	17.36	19.36	.12
$\mu_{R_6^\alpha}$	=	5.74	6.23	6.77	
$\sigma^2_{R_6^\alpha}$	=	21.00	26.44	33.23	

TABLE XIX

Areal Coverage of Hurricanes

Used To Find α

Hurricane	Year	Diameter (miles)	Areal Coverage (sq.mi.)	Mean Telephone Density $\left(\frac{\text{Stations}}{\text{sq. mi.}}\right)$
Edna	1954	250	21,000	111
Hazel	1954	83	45,000	60
Connie	1955	160	25,000	56
Diane	1955	100	5,000	6
Ione	1955	80	14,000	6
Flossy	1956	51	6,000	26
Audrey	1957	44	9,000	21
Gracie	1959	100 (est)	10,000	21
Donna	1960	80	39,000	88
Carla	1961	180	19,000	12

TABLE XX

Zonal Mean and Variance

(Analytically Determined from Equs. 9-5 and 9-6)

	$\bar{X}_i$ Mean	$\sigma_{X_i}^2$ Variance x 10^8
Zone 1, α_L	19675	10.005×10^8
Zone 1, α_M	21307	12.427 "
Zone 1, α_H	23103	15.445 "
Zone 2, α_L	38021	32.691 "
Zone 2, α_M	41317	40.433
Zone 2, α_H	44918	50.060
Zone 3, α_L	28674	21.977
Zone 3, α_M	30628	26.401
Zone 3, α_H	32791	31.818
Zone 4, α_L	22145	9.765
Zone 4, α_M	23826	11.823
Zone 4, α_H	25675	14.349
Zone 6, α_L	46609	20.620
Zone 6, α_M	50588	25.400
Zone 6, α_H	54972	31.740

APPENDIX II

Hardness Factor (α)

The symbol α in the damage model has been referred to as a hardness factor. This symbol has two meanings; one meaning mathematically and still another in physical terms. Mathematically, α is a constant whose optimal value minimizes the squared error about a curve passing through the historical damage data. This curve is defined by the damage model

$$X = AR^{\alpha}$$

and it is expected that α will generally range between zero and one although this restriction was not placed on α in minimizing the squared error.

In physical terms, when $\alpha = 1$, the entire product in the area will be damaged or $X = AR$; when $\alpha = 0$, the damage will be one unit for each unit of area or $X = A$. Looking at α as a hardness factor, when $\alpha = 1$, the product has no hardness to hurricanes and when $\alpha = 0$, the product is completely hardened to hurricane damage. However, when $\alpha = 0$, it was hypothesized that there would be damage regardless of how well the product was hardened against hurricanes. This hypothesis was the justification for raising R to α power rather than making the model linear by multiplying AR by α. It was found that the squared error for the linear model was greater than for the model used in this paper thus decreasing the prediction error.

As pointed out in Section (XI), the user of the damage model has the option to adjust α to a particular geographical area. If it is felt that the product in a certain area is less susceptable to hurricane winds than the average, the user may decrease α to decrease the mean of the damage distribution and vice versa.

Finally it is felt that some effort should be put forth in determining a good estimate for α. As shown in the model testing (Section X), the degree of uncertainty in the damage distribution is proportional to the degree of uncertainty in α.

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